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Slash-and-char: An ancient agricultural technique holds new promise for management of soils contaminated by Cd, Pb and Zn

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ABSTRACT

Heavy metal contamination of agricultural soils is of worldwide concern. Unfortunately, there are currently no efficient and sustainable approaches for addressing this concern. In this study, we conducted a field experiment in which an agricultural soil highly contaminated by cadmium (Cd), lead (Pb) and zinc (Zn) was treated on-site by an ancient agricultural technique, 'slash-and-char', that was able to convert the biomass feedstock (rice straw) into biochar in only one day. We found evidence that in comparison to the untreated soil, the treated soil was associated with decreased bioavailability of the heavy metals and increased vegetable yields. Most importantly, the treatment was also coupled with dramatic reductions in concentrations of the heavy metals in vegetables, which made it possible to produce safe crops in this highly contaminated soil. Collectively, our results support the idea that slash-and-char offers new promise for management of soils contaminated by Cd, Pb and Zn.

1. Introduction

One of the consequences of anthropogenic activities is that the concentrations of heavy metals in various environmental matrices (especially soil) have increased worldwide (Adriano, 2001; Nriagu and Pacyna, 1988). In Western Europe, over 300 000 sites are reported to be contaminated by heavy metals (McGrath et al., 2001); whereas, in the USA this figure is double (McKeehan, 2000). The problem of heavy metal contamination in soils is even more challenging in developing countries. For example, it has been estimated that 19 360 ha of land in Bulgaria remain contaminated by heavy metals (Puschenreiter et al., 2005) and approximately 20 000 000 ha of arable soils in China are similarly contaminated (Wei and Chen, 2001). Due to their non-degradability, heavy metals are extremely persistent in the environment (Adriano, 2001). Moreover, heavy metals in contaminated agricultural soils can be accumulated in edible parts of crop plants, thereby moving into the human food chain and representing a serious potential threat to human health (McLaughlin et al., 1999). For these reasons, heavy metal contamination of agricultural soils is of worldwide concern.

Current available approaches for treating soils contaminated by heavy metals can be roughly divided into two major groups: *ex situ* and *in situ* technologies (Abou-Shanab, 2011). The former group includes bulk excavation and landfilling, acid washing, etc. These *ex situ* methods are mainly suitable for relatively small areas, but tend to be prohibitively expensive, and cause the disruption or total loss of soil structure (Abou-Shanab, 2011). The latter group includes solidification/stabilization and phytoextraction. These *in situ* approaches are generally considered to be less expensive, compared to *ex situ* methods (Abou-Shanab, 2011). Their applications, however, have suffered considerably from their respective disadvantages. For example, many stabilization/solidification processes may lead to a substantial increase in soil volume and may also hinder future site use (Abou-Shanab, 2011), whilst phytoextraction tends to require dozens or even hundreds of years to clean up a highly or multiply metal-contaminated soil (Robinson et al., 2015). Therefore,

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there is a great need to develop new approaches that can be used not only to efficiently reduce the environmental health risks associated with soils contaminated by heavy metals but also to simultaneously maintain the basic functions of these soils.

Slash-and-char, an alternative to slash-and-burn, is an ancient, remarkably simple agricultural technique which is believed to have been employed by pre-Columbian Amerindians between 500 and 2500 years ago to create the well-known 'Amazonian dark earths' (Lehmann et al., 2003a). In fact, this technique (or its analog) is still used in modern society (FAO, 1987; Glaser, 2007). More specifically, slash-and-char refers to the agricultural technique that typically consists of the following three steps: (1) cutting of above-ground biomass (usually forests), which is also known as land clearance; (2) drying the cut biomass and converting it into biochar on-site in simple earthen mounds or pits, and (3) mixing the biochar produced directly into its surrounding soil, which is subsequently used for crop production (Glaser, 2007; Lehmann et al., 2003a). One of the most important features distinguishing this technique from slash-and-burn is that the slashed biomass is converted into biochar by low-temperature incomplete combustion (smoldering) in an oxygen-poor environment rather than being fully burnt into an ash (Glaser, 2007; Lehmann et al., 2003a). Soils generated by this agricultural technique are generally characterized by their higher contents of biochar, higher levels of organic matter, higher pH values, and a greater retention of cations than in the surrounding soils (Downie et al., 2011; Glaser, 2007; Lehmann et al., 2003b; Sheil et al., 2012). All these characteristics are desirable to reduce the bioavailability of heavy metals in soil (Adriano, 2001), thus raising at least two intriguing possibilities: (1) that biochars produced from smoldering biomass feedstocks can be applied to stabilize heavy metals in contaminated soils; and (2) that this simple agricultural technique *per se* (or its analog) can be used directly to deal with heavy metal contaminated soils.

Over the past few years, increasing attention has been paid to the potential roles of biochars in remediation of heavy metal-contaminated soils (Ahmad et al., 2014; Beesley et al., 2011). Although to date relatively few studies have attempted to determine the efficiency of biochars in reducing the bioavailability of heavy metals in contaminated soils under field conditions (Bian et al., 2014; Zheng et al., in press), some important technical advances have emerged (Ahmad et al., 2014; Beesley et al., 2011). Firstly, a variety of biochars derived from not only biomass feedstocks but also non-biomass wastes (e.g. sludge and manure) have been shown to be able to immobilize heavy metals in contaminated soils (Khan et al., 2013; Park et al., 2011). Secondly, the efficiency of biochars is influenced by various factors. For example, pyrolysis temperature has been proven to substantially affect the ability of biochar to sequester heavy metals in contaminated soils (Uchimiya et al., 2011). Thirdly, it has been found that the same type of biochar can have contrasting effects on the mobilities of different heavy metals in contaminated soils. For example, Beesley et al. (2010) reported that the amendment of wood-derived biochar to a soil contaminated by multiple elements led to reduced mobilities of Cd and Zn, but elevated mobilities of arsenic and copper (Cu).

Unlike biochar, the potential of slash-and-char *per se* (or its analog) for remediating heavy metal contaminated soils has not yet been investigated. This potential deserves careful empirical studies because in the slash-and-char process, biochars can be readily obtained on site with simple earthen mounds/pits and directly amended to contaminated soils, being independent of machine tools. The simplicity of this technique allows immediate implementation and also likely makes it particularly attractive to many developing countries where soil heavy metal contamination is a major environmental problem.

In this study, we attempted to determine the potential of slash-and-char by conducting a field experiment on a farm where the soil is highly contaminated by Cd, Pb and Zn. The top 20 cm of soil layer was excavated and treated by slash-and-char on site. In this sense, this technique could be considered as an *ex situ* approach. The rice straw produced on the same farm was used as the biomass feedstock for slash-and-char, so that cutting of rice straw can be seen as a 'land clearance' step. The excavated contaminated soil was used to cover the biomass feedstock, thereby creating an oxygen-poor environment for conversion the biomass feedstock into biochar. After one day of treatment with slash-and-char, the excavated soil was refilled on site and subsequently used for vegetable production. More specifically, this study aimed to address the following three questions: (1) whether slash-and-char can be used to immobilize heavy metals in contaminated soils? (2) whether slash-and-char can be applied to increase the productivity of vegetables growing in contaminated soils? and (3) whether slash-and-char can be employed to reduce heavy metal uptake by vegetables?

2. Materials and methods

2.1. Study site

This study was conducted on a farm near the Lechang Lead/Zinc Mine, which is located in the north of Guangdong Province, China (25°13′N, 113°35′E). The region is characterized by a subtropical monsoonal climate with an annual average rainfall of about 1500 mm and an annual average temperature of about 20 °C. The main soil type in this region is a red loam soil. Our previous studies have shown that the farmland surrounding the mine was highly contaminated by Cd (2–30 mg kg^{-1}), Pb (325–4317 mg kg^{-1}) and Zn (120–3026 mg kg^{-1}), and that the heavy metals taken up by crops growing in the farmland often posed significant health risks to inhabitants (Yang et al., 2004, 2006, 2008).

2.2. The slash-and-char treatment

An area of 300 m^2 delimited at the centre of the farm was used for our experiments. In March 2013, the experimental area was ploughed by cattle to about 20 cm depth and the ploughed soil left to dry naturally. When the soil dried to a moisture content of < 10%, it was broken into clods (< 5 cm in diameter) and fine soil using a shovel, piled up, mixed thoroughly and divided into two portions: one treated with slash-and-char and the other kept untreated. Before the soil was divided, 30 soil samples were collected to evaluate the basic chemical properties of the untreated soil. Local farmers were employed to help to perform the slash-and-char treatment. Dry rice straw (with a moisture content < 5%) was collected from the same farm and used as biomass feedstock for the treatment. The concentrations of Cd, Cu, Pb and Zn in the rice straw were 1.06, 0.92, 9.71 and 84.6 mg kg^{-1} (on a dry weight basis, DW) respectively, which all fell well within values given in the literature (Zhou et al., 2015). The dry weight percentages of O, C, H, N and S in the rice straw were 42.0%, 38.7%, 6.04%, 0.59% and 0.28% respectively, being within the normal range (Liu et al., 2011). According to the practical experience of local farmers, a mass ratio of 1:10 biomass feedstock:soil (w/w) was chosen. Assuming that the annual yield of rice straw is 20 t ha^{-1} (DW; Zhao et al., 2012), that produced on 1 ha of land can be used to incorporate into the top 20 cm soil layer of approximately 100 m^2 of land with a bulk soil density of 1.2 g cm^{-3} (Zhang et al., 2005). If 20 t of rice straw are converted into biochar with a pyrolysis machine giving an average biochar yield of 30% (Uchimiya et al., 2011) and the biochar is amended to soil at the widely tested rate of 5% w/w (Khan et al., 2013; Park et al., 2011; Uchimiya et al., 2011), the biochar produced can be employed to treat the top 20 cm soil layer of 50 m^2 of land (i.e. 120 t of soil). Nonetheless, enormous quantities of rice straw are available; for example, the estimated annual yield of rice straw in China is approaching 2 000 000 t (Liu et al., 2011). The biomass feedstock was prepared as rice straw bundles in the shape of a cylinder with a diameter of 10–15 cm and a height of 20–40 cm and tied with straw. As a first step of the treatment, a cross ditch (90–100 cm in diameter, 25–30 cm wide and 25–30 cm deep) was dug into the ground. The second step was to cover the ditch with a 15–20 cm layer of biomass feedstock. In this step, an opening near an end of the cross ditch was left for lighting the smoldering fire. The third step was to cover the layer of biomass feedstock with a 15–20 cm layer of the soil prepared for the treatment. Subsequently, the second step (covering the soil layer with a layer of biomass feedstock) and the third step were repeated in turn until the 'biomass-soil' stack (in the shape of a cone with a base diameter of 90–100 cm) reached a height of about 100 cm. To facilitate the smoldering during the treatment, some large clods (1 cm < diameter < 5 cm) were added to the inner soil layers, whereas the outermost soil layer comprised small clods (< 1 cm diameter) and fine soil. The last step was to start the smoldering fire by igniting the biomass feedstock from the opening at the bottom of the 'biomass-soil' stack. Some small and open flames may be seen from the stack during the treatment; if so, fine soil should be used to cover the flames. The smoldering will be complete within 24 h. The stack can then be uncovered, broken into small fragments or particles, mixed thoroughly and used for vegetable cultivation. For a clearer understanding of the slash-and-char technique described in this study, a schematic diagram showing the major steps is provided (Fig. 1).

To make the target soil to be treated fully with slash-and-char, 30 'biomass-soil' stacks were established. Among these, three were selected at random to: (1) determine the concentrations of heavy metals in the smoke emitted during the treatment; (2) quantify the biochar generated during the treatment; and (3) track the temperatures of the stacks during the treatment. For the first objective, smoke was sampled according to the method described by Betha et al. (2013). The sampling was commenced when the smoke emission became stable (i.e. about 4 h after starting the smoldering fire) and lasted 6 h. To achieve the second objective, biochar was collected and weighed after the stacks were uncovered and allowed to cool to ambient temperature. For the third objective, three thermocouples were inserted into the outer, middle and inner parts of each of the stacks and the temperatures were recorded at 4, 8 and 24 h after the initiation of the treatment. The soil from these three stacks was not used for the subsequent experiment, since the biochar had been removed from the stacks.

2.3. Vegetable cultivation

After the soil was treated with slash-and-char, one soil sample was collected from each of the 30 'biomass-soil' stacks to determine the basic chemical properties of the treated soil. Our experimental area was divided into 6 blocks, each of which was further divided into 8 plots (2 m × 2 m). We manipulated both soil and vegetable types in a fully factorial experimental design. Soil treatment had 2 levels: the untreated soil and the treated soil whilst the vegetable treatment had 4 levels (i.e. 4 very popular leaf vegetables in the region): *Brassica parachinensis* (Vegetable I), *Brassica chinensis* (Vegetable II), *Brassica juncea* var. *crispifolia* (Vegetable III) and *Brassica oleracea* var. *oleracea* (Vegetable IV). This design yielded 8 treatment combinations, each of which was replicated 6 times in 6 plots. The treatments were assigned to plots in a fully randomized manner. The plots for 'the treated soil' were covered with the soil treated with slash-and-char to a depth of 15–20 cm whilst, those for 'the untreated soil' were covered with the untreated soil to a similar depth. In August 2013, the seeds of the 4 vegetables were planted directly into the plots. Field management (including irrigation, fertilization, insect and weed control) was conducted according to local agronomic practices. More specifically, N, P and K fertilizer application rates were 150, 30 and 100 kg ha^{-1}, respectively. Forty days after sowing, the 4 vegetables were harvested individually, washed thoroughly, divided into below-ground and above-ground parts (i.e. non-edible and edible parts), weighed and

Table 1
Comparison of basic chemical properties of the untreated and treated soils.

	Untreated soil	Treated soil	*P*-value
pH	7.0 ± 0.01	7.4 ± 0.01	< 0.01
EC (μs cm^{-1})	326 ± 9.8	1809 ± 14	< 0.01
Total Cd (mg kg^{-1})	6.0 ± 0.13	5.7 ± 0.11	> 0.05
Total Cu (mg kg^{-1})	100 ± 1.2	97 ± 1.4	> 0.05
Total Pb (mg kg^{-1})	1988 ± 37	1925 ± 19	> 0.05
Total Zn (mg kg^{-1})	3833 ± 92	3803 ± 54	> 0.05
NH_4–N (mg kg^{-1})	81 ± 6.2	132 ± 6.5	< 0.01
NO_3–N (mg kg^{-1})	17 ± 2.7	18 ± 0.88	> 0.05
Available P (mg kg^{-1})	62 ± 3.7	172 ± 7.4	< 0.01
Available K (mg kg^{-1})	100 ± 5.7	2208 ± 70	< 0.01

Data are presented as means ± S.E. (n = 30). *P*-values are from one sample *t*-tests.

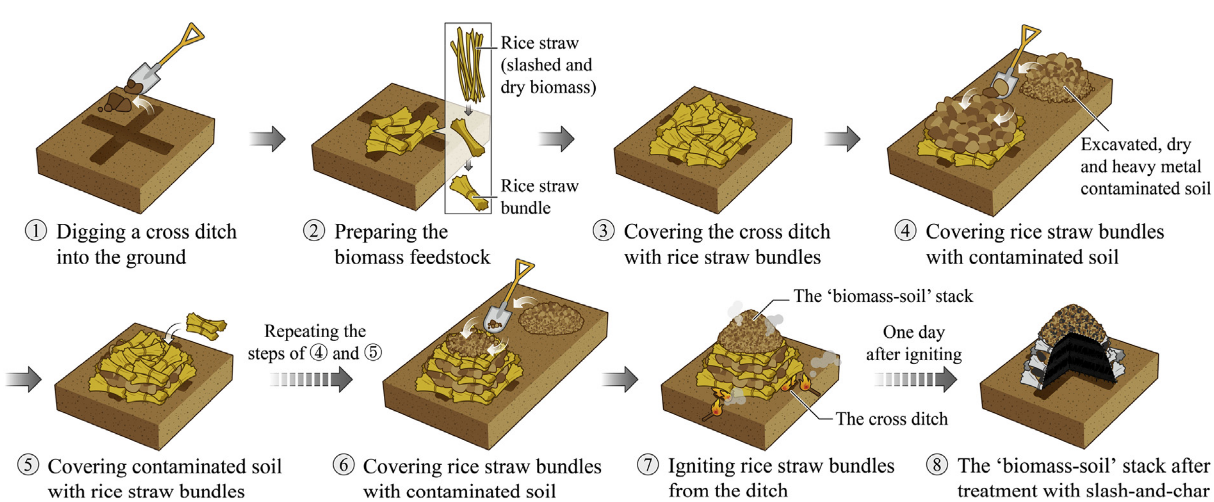

Fig. 1. Schematic diagram showing the major steps of the slash-and-char technique described in this study.

oven-dried at 70 °C for 24 h.

2.4. Chemical analysis

For determination of the total concentrations of heavy metals in the soils, Method 3052 recommended by the US EPA was used. For evaluation of the bioavailability of heavy metals in the soils, diethylenetriaminepentaacetic acid (DTPA)-extractable heavy metals were determined according to the method proposed by Lindsay and Norvell (1978). Other basic chemical properties of the soils, including pH, electrical conductivity (EC), ammonium-nitrogen (NH_4–N), nitrate-nitrogen (NO_3–N), available phosphorus (P) and available potassium (K) were determined using standard methods. The method proposed by Miller (1998) was applied to analyze the heavy metals in the vegetable samples. The heavy metals in the particulate matter of smoke emitted during the slash-and-char treatment were determined according to the procedure described by Betha et al. (2013) with a minor modification (i.e. concentrated HNO_3 rather than other extractants was used). The concentrations of heavy metals in the digested solutions and extractants were determined by atomic absorption spectrometry (Z-5300, Hitachi, Tokyo, Japan).

2.5. Statistical analysis

All statistical analyses were performed using SPSS version 18.0 software (SPSS, Chicago, USA). The significant differences between the untreated soil and the treated soil in basic chemical properties were determined by one sample *t*-tests, where the average of the 30 samples of the untreated soil was considered as 'Test Value'. Any significant differences between the two soils in the productivity of vegetables and concentrations of heavy metals in edible parts of vegetables were tested by ANOVA followed by LSDs.

3. Results and discussion

3.1. The untreated soil

Concentrations of total Cd, Pb and Zn in the untreated soil were extremely high (Table 1), being 20×, 6.6× and 15× greater, respectively, than the Environmental Quality Standards for Soil set by the State Environmental Protection Administration of China (SEPAC, 1995). These concentrations also exceeded the respective limits set by the European Union (EU, 2000) by a factor of 4, 19 and 17, correspondingly. It was thus apparent that this highly contaminated soil was unsuitable for crop production and should be treated as soon as possible to reduce the associated environmental health risks. Unfortunately, the soil was still used for crop production, presenting a significant health risk to the inhabitants of the surrounding area. This situation is indeed quite normal in many developing countries (Adriano, 2001; McGrath et al., 2001; McKeehan, 2000; Puschenreiter et al., 2005; Wei and Chen, 2001). There are two major reasons. On the one hand, the land required for food production to feed the growing population remains a great challenge in these countries. On the other hand, the efficient and sustainable remediation approaches seem to be inapplicable (see Introduction section for details).

3.2. Reduced bioavailability of heavy metals in the soil treated with slash-and-char

After one day of slash-and-char treatment, concentrations of total Cd, Cu, Pb and Zn were slightly but not significantly ($P > 0.05$) lower in the treated soil than in the untreated soil (Table 1). These results could be explained by a dilution effect derived from the biomass feedstock (i.e. rice straw), which was added at a mass ratio of 1:10 biomass:soil for treating the soil with slash-and-char (see Materials and methods for details). Note also that approximately 75% of the biomass is expected to be lost during charring (Lehmann, 2009). Indeed, we found that only 10–15% of the initial biomass (on average 12%, equivalent to 30% of the carbon in the initial biomass) was converted into forms similar to biochar. This conversion percentage was much greater than those (1.7–3%) observed for typical slash-and-burn systems (Glaser et al., 2002), whilst it seems slightly lower than those (about 14%) recorded for charring woody biomass into biochar using methods similar to ours (i.e. simple earthen pits or mounds; Coomes and Burt, 2001).

Remarkably, DTPA-extractable concentrations of Cd, Cu, Pb, and Zn were significantly ($P < 0.01$) lower in the treated soil than in the untreated soil (Fig. 2), indicating that the bioavailability of the heavy metals in the soil has been greatly reduced. One possible explanation for this result lies in the presence of the biochar in the treated soil (about 1% by weight of the soil, as mentioned above), given the ability of biochar to absorb various kinds of contaminants (Ahmad et al., 2014). This, however, does not rule out other explanations. Because the evidence currently available indicates that the addition of biochar to contaminated soil is favorable for the immobilization of Cd, Pb and Zn, but both immobilization and mobilization of Cu (Ahmad et al., 2014). In fact, there are at least

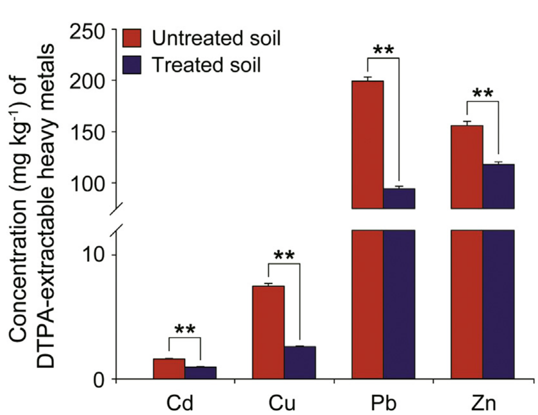

Fig. 2. Concentration (mg kg^{-1}) of DTPA-extractable heavy metals in the untreated and treated soils. Data are presented as means ± S.E. (n = 30). Results of the one sample *t*-tests are shown: *$P < 0.05$; **$P < 0.01$.

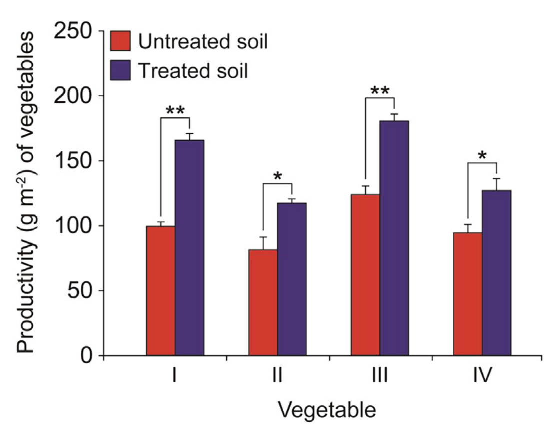

Fig. 3. Productivity (g m^{-2}) of vegetables growing in the untreated and treated soils. Productivity referred to dry weight biomass of edible (i.e. above-ground) parts. Data are presented as means ± S.E. (n = 6). Vegetable I, II, III and IV referred to *Brassica parachinensis*, *Brassica chinensis*, *Brassica juncea* var. *crispifolia* and *Brassica oleracea*. var. *oleracea*, respectively. Results of the ANOVA followed by LSDs are shown: *$P < 0.05$; **$P < 0.01$.

two additional possible explanations. One may be the elevated concentration of available P in the treated soil (Table 1), which can facilitate the immobilization of heavy metals (Cao et al., 2003). The other explanation is related to the elevated pH in the treated soil (Table 1), considering that the bioavailability of heavy metals in soil tends to be lower at higher pHs (Adriano, 2001). The increase in soil pH induced by slash-and-char can be attributed to several causes. Firstly, soil heating (100–600 °C in our case, see Materials and methods for details) is generally associated with the denaturation of organic acids (Certini, 2005). Secondly, components of ash (e.g. calcium carbonate and hydroxide) originating from biomass combustion are mainly alkaline (Dowman, 1970). Thirdly, biochars generated by various methods are generally alkaline (with a mean pH value of 8.9; Ahmad et al., 2014).

3.3. *Elevated vegetable productivity of the soil treated with slash-and-char*

Treatment with slash-and-char increased the productivity (above-ground biomass, i.e. edible biomass production) of the four leaf vegetables by 34–67% (Fig. 3). These results are comparable to the observations made by Lehmann et al. (2003b) who found that an archaeological Anthrosol of the Central Amazon basin (known as 'Amazonian dark earths') which is thought to have been created by pre-Columbian populations with slash-and-char (or its analogs), increased the biomass production of both cowpea (*Vigna unguiculata*) and rice (*Oryza sativa*) by 38–45%, as compared to a surrounding soil (i.e. the Ferralsol) with no anthropogenic A horizon. There are at least three possible mechanisms that could have driven the elevated vegetable productivity observed in this study. The first is related to the increased availability of plant nutrients (including NH_4–N, P and K), whose concentrations were found to be significantly ($P < 0.01$) higher in the treated soil than in the untreated soil (Table 1). Similarly, Lehmann et al. (2003b) showed that the higher biomass production of cowpea and rice in the Anthrosol compared to the Ferralsol could largely be attributed to improved availability of plant nutrients (especially P). The second possible explanation seems to lie in the reduced phytotoxicity (as indicated by DTPA-extractable concentrations) of heavy metals in the treated soil (Fig. 2). However, the extent to which the increased vegetable productivity can be attributed to the reduced heavy metal phytotoxicity associated with the biochar derived from rice straw during the slash-and-char treatment is questionable. It has been repeatedly demonstrated that the addition of biochar derived from agricultural residual biomass was not very effective in improving the growth of plants growing in heavy metal contaminated soils (Fellet

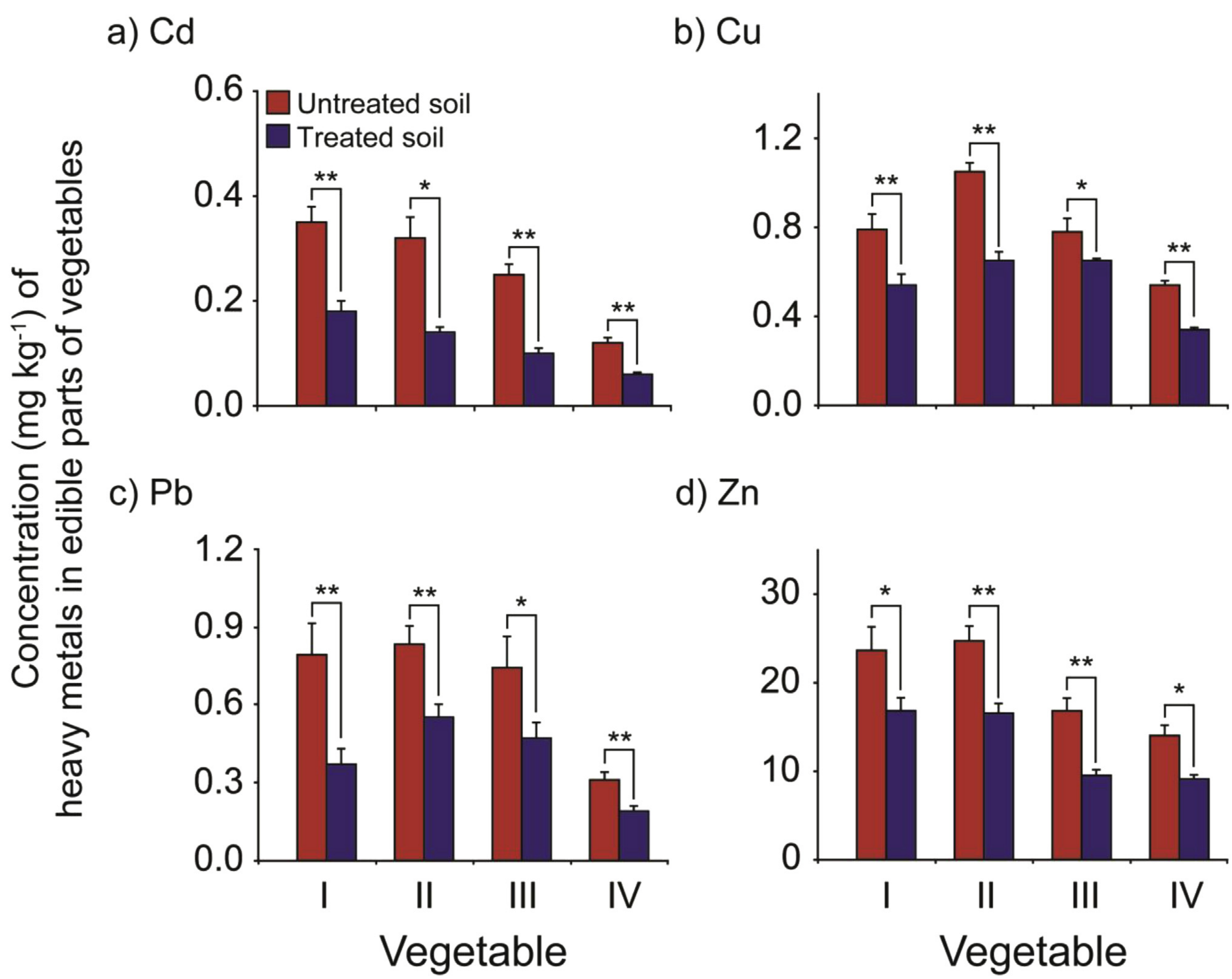

Fig. 4. Concentrations (mg kg^{-1}) of heavy metals in edible parts of vegetables growing in the untreated and treated soils. Data (means ± S.E., n = 6) are presented on a fresh weight basis. Vegetable I, II, III and IV referred to *B. parachinensis*, *B. chinensis*, *B. juncea* var. *crispifolia* and *B. oleracea*. var. *oleracea*, respectively. Results of the ANOVA followed by LSDs are shown: $^{*}P < 0.05$; $^{**}P < 0.01$.

et al., 2014; Karami et al., 2011; Park et al., 2011). It should be noted that the biomass feedstock (i.e. rice straw) employed to generate biochar in this study is different from those (e.g. tree pellets) of the previous studies. The third possible explanation involves the high nutrient retention capacity of the treated soil (Lehmann et al., 2003b). In this study, the doses of N, P and K fertilizers applied to the soils are expected to be enough to support the growth of the vegetables (Lv et al., 2009). However, the potential risk of fertilizer leaching in this area is high, due largely to its abundant rainfall (Li et al., 2011). Nonetheless, it remains an open question whether the biochar derived from rice straw during the slash-and-char treatment can effectively improve the nutrient retention capacity of the treated soil, thereby increasing vegetable productivity. There is considerable evidence suggesting that the application of biochar derived from agricultural residual biomass is not an efficient approach to enhance crop production even in uncontaminated soils (Tammeorg et al., 2014). Further research is required to discern the relative importance of the three mechanisms mentioned above.

3.4. Reduced concentrations of heavy metals in vegetables growing in the soil treated with slash-and-char

In good agreement with our results on the bioavailability of heavy metals in the soils, we showed that the concentrations of heavy metals were significantly ($P < 0.05$) lower in all the four vegetables (edible parts) growing in the treated soil compared to those in the untreated soil (Fig. 4). More importantly, the concentrations of both Cd and Pb in one of the four leaf vegetables (i.e. vegetable IV, Fig. 4) growing in the treated soil were reduced to a level lower than the respective limits (i.e. 0.2 mg kg^{-1} for Cd and 0.3 mg kg^{-1} for Pb) set by both the Ministry of Health of China (MHC, 2005) and the EU (2006), whereas those of Cd and Pb in all the four vegetables growing in the untreated soil exceeded the Chinese and European limits. Currently, no maximum limits have been set for Cu and Zn in crops. It can be thus concluded that slash-and-char makes it possible to produce safe vegetables in this soil highly contaminated by Cd, Pb and Zn. The currently available evidence from field experiments, however, indicates that a similar effect cannot be achieved by the addition of biochar (Bian et al., 2014; Zheng et al., in press).

3.5. Implications and limitations

Due to its technical simplicity, slash-and-char may cause pollution by directly releasing smoke into the atmosphere. Fortunately, we found that the concentrations of heavy metals (e.g. 0.02 mg Pb m^{-3}) in the smoke emitted during the slash-and-char were much lower than the respective emission limit values (e.g. 0.50 mg Pb m^{-3}) set by both the SEPAC (1996) and the EU (2010). Keeping in mind that if the agricultural residual biomass (such as rice straw in our case) is not used for slash-and-char, it would be either burned in the field into ash or added to fields directly, so leading to the release of larger amounts of smoke and/or green house gases (primarily CO_2 and CH_4; Woolf et al., 2010). Indeed, it has been estimated that substituting slash-and-char systems for slash-and-burn agriculture will offset up to 12% of current anthropogenic CO_2–C equivalent emissions per year (Lehmann et al., 2006; Woolf et al., 2010). In this sense, slash-and-char seems to be a 'killing two birds with one stone' strategy. However, further studies are required to evaluate the generality of our findings. More specifically, an important next step needs to determine the extent to which our findings can be applicable to different soil environments and crop types. In addition, it remains worthy to determine whether a similar effect can be achieved when other agricultural biomasses (e.g. brush and tree) are used as biomass feedstock for slash-and-char. It will also be crucial to explore the sustainability of the beneficial effects of slash-and-char observed in this study, although there is evidence that the soils generated by slash-and-char maintain their fertility over a long period of time (Lehmann et al., 2006).

4. Conclusions

This study presented evidence to support the idea that an ancient, remarkably simple agricultural technique has the potential to provide an efficient, low-cost and sustainable strategy for dealing with the worldwide concern derived from agricultural soils highly contaminated with multiple heavy metals. Our findings may be practically significant, especially considering that a huge amount of agricultural waste biomass exists in many regions around the world (Woolf et al., 2010) and many farmers in these regions are very familiar with either the slash-and-char practice or its analogs (Lehmann et al., 2006).

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