Environmental Pollution 205 (2015) 333–339

Contents lists available at ScienceDirect

Environmental Pollution

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

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

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ARTICLE INFO

Article history:
Received 15 March 2015
Received in revised form
30 May 2015
Accepted 1 June 2015
Available online xxx

Keywords:
Slash-and-char
Ancient agricultural technique
Cd
Pb
Zn
Safe crop production
Multiple contamination
Rice straw
Biochar

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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http://dx.doi.org/10.1016/j.envpol.2015.06.017
0269-7491/

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