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The effects of biochar addition on phosphorus transfer and water utilization efficiency in a vegetable field in Northeast China

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ABSTRACT

The excessive application of fertilizer has become a serious problem for vegetable farming in China and aggravates agricultural non-point pollution. As a soil amendment, biochar has obtained worldwide attention. Irrigation and fertilization management also play an important role in controlling agricultural non-point pollution. To investigate the effects of biochar addition, irrigation and fertilization management on phosphorus (P) leaching as well as water utilization efficiency (WUE) in vegetable fields in northeast China, a field experiment with three treatments, i.e., regular fertilization and irrigation (CK), regular fertilization and irrigation with biochar addition (100WF + B) and 20% reduction of chemical fertilizers and irrigation compared to 100WF + B (80WF + B), was conducted. The P leaching amounts in 100WF + B and 80WF + B were only 15.91% and 11.36%, respectively, of that in CK. The P uptake amounts in the three treatments in descending order were 100WF + B, 80WF + B, and CK. The WUE in 100WF + B and 80WF + B were 15.3 and 25.2 kg/(ha mm) higher, respectively, than that in CK. There were no significant differences between the yield of CK and 80WF + B. The yield of 100WF + B was 3.4 t/ha higher than the yield of CK. Biochar significantly increased WUE, yield, TP (total phosphorus) and AP (available phosphorus) contents in the surface layer as well as P uptake and decreased P leaching when comparing 100WF + B to CK. Fertilization and irrigation reduction decreased P leaching and significantly increased WUE, but the yield was affected when comparing 80WF + B to 100WF + B. Biochar combined with fertilization and irrigation reduction significantly increased WUE and decreased P leaching without affecting yield when comparing 80WF + B to CK.

1. Introduction

With the change in the Chinese diet, the consumption of vegetables is increasing in China. To keep abreast of this trend and provide more vegetables to society, vegetable farming is increasing in China. In practice, excessive fertilizers have been applied to vegetative soil for high profits. The excessive fertilizers can lead to an excess of fertilizer residues and nutrients leaching with down-flow irrigation, which causes a decrease in environmental water quality and agricultural non-point source pollution (Huang et al., 2009; Sun et al., 2012).

Owing to its unique physical and chemical properties, biochar can increase fertilizer utilization efficiency, enhance water holding capacity, increase WUE and reduce nutrient leaching, which could help to reduce agricultural non-point pollution (Busscher et al., 2010; Glaser et al., 2002; Lehmann et al., 2003). It has been well-established that biochar has positive effects on P availability and reducing P loss in soils by changing the adsorption and desorption of P (Guan et al., 2013; Xu et al., 2014; Zhao et al., 2017). Column leaching experiments have verified the effects of biochar addition on P leaching (Kumari et al., 2014). Field experiments also proved the positive effects of biochar addition on the effective P content (Wang et al., 2016). In a 3-year maize field experiment, biochar addition slightly increased the WUE in the first year and significantly increased the WUE in the last two years in Cumuli-Ustic Isohumosols (Xiao et al., 2016). Similar effects of biochar addition were found in a brown loam rice field and Mollisol maize field (Liu, 2016; Zhu et al., 2018). As fertilization and irrigation are two

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key factors in agricultural non-point pollution, fertilization and irrigation management becomes an important way to control agricultural non-point pollution (Yang et al., 2013). It has been reported that irrigation and fertilization management increased nutrient utilization and WUE (Tang et al., 2018; Zhang et al., 2018). Meanwhile, little is known regarding the effects of biochar as well as irrigation and fertilization management on P transfer and WUE in Mollisol vegetable fields.

In the northeast China Mollisol region, due to the climate, the duration of field vegetable farming can be very short annually, and facility vegetable farming is getting popular, which is increasing the need for irrigation water and the risk of agricultural non-point pollution. An experiment in an eggplant (*Solanum melongena*) planting greenhouse was conducted to investigate the effects of biochar as well as irrigation and fertilization management on P transfer and WUE in a vegetable field in northeast China.

2. Materials and methods

2.1. Site description

The experiment was conducted in the Institute of Horticulture, Heilongjiang Academy of Agricultural Sciences, Harbin, China (45°37.836′N, 126°39.050′E). The climate is a temperate continental monsoon climate, with cold winters and hot summers. The mean annual temperature is 4.25 °C, with the lowest temperature of −42.6 °C and the highest temperature of 39.2 °C. The mean annual precipitation is 569.1 mm, with 60%–70% occurring in the summer.

The greenhouses were built in 2002 and are oriented south–north, with an area of 324 m^2 (12 m in width and 27 m in length). Eggplant has been planted in the greenhouses since 2002. The eggplant variety was *Longqie 8* in 2017. According to the soil texture classification system of the USDA, the soil is Mollisol. The initial physical and chemical properties of the soil profile are listed in Table 1.

2.2. Experimental design

On March 10, 2017, eggplant seeds were sowed in float trays for the nursery. The soil was tilled, and the seedbeds (1 m in width, 50 cm between two seedbeds) were prepared before eggplant transplantation on May 3, 2017. A drip tape was placed in the middle of the seedbed, and then the bed was covered with black polyethylene mulch (1.2 m in width). Two rows of eggplant were transplanted with 50 cm spacing in between rows and lines.

The treatments were designed as follows: (1) regular fertilizer and irrigation amount (CK), (2) biochar addition with regular fertilizer and irrigation amount (100WF + B), and (3) biochar addition with 20% reduction of chemical fertilizers and the irrigation amount compared to CK (80WF + B). The specific fertilization and irrigation management of different treatments can be seen in Table 2. Based on a previous study, the reduction of chemical fertilizers and irrigation is set at 20% (Zhou et al., 2015). Biochar was added into soil in combination with basal fertilizers. The top-dressing fertilizer was applied in a hole near each plant. When eggplants entered the last picking stage, irrigation was terminated.

Table 1
Initial soil properties.

Depth (cm)	SOC ($g\,kg^{-1}$)	TN ($g\,kg^{-1}$)	TP ($g\,kg^{-1}$)	pH (H_2O)	Bulk Density (g/cm^3)
0-20	26.9	2.5	2.1	6.93	1.07
20-40	18.3	1.7	1.1	6.45	1.28
40-60	14.8	1.3	0.6	6.80	1.25
60-80	9.8	0.9	0.4	6.85	1.33
80-100	9.6	0.8	0.6	6.75	1.41

SOC: soil organic carbon; TN: total nitrogen; TP: total phosphorus.

Table 2
Specific fertilization and irrigation managements of different treatments.

		CK	100WF + B	80WF + B
Biochar addition (t/ha)		0	30	30
Basal fertilizer (t/ha)	Organic fertilizer	5	5	5
	N	72	72	57.6
	P_2O_5	72	72	57.6
	K_2O	110	110	88
Dressing fertilizer in early fruit stage (t/ha)	N	70	70	56
Dressing fertilizer in the full bearing period (t/ha)	N	23	23	18.4
	K_2O	113	113	90.4
Irrigation after transplanting (m^3/ha)		27	27	27
Irrigation every 7 to 10 days when the plant recovered (m^3/ha)		45	45	45

Commercial organic fertilizers, urea (with 46% N), superphosphate (with 12% P_2O_5) and potassium sulphate (with 50% K_2O) were used as basal and topdressing fertilizers, and drip irrigation systems were applied in this experiment. Based on previous studies, when the amount of biochar applied is 30 t/ha, the highest yield can be reached (Liu et al., 2018; Zhong-Yang et al., 2015). Biochar was made from fruit wood under 600 °C. The total C, total P and pH of biochar are 715 g kg-1, 1.4 g kg-1 and 8.87, respectively.

A completely randomized design with three replications was used. The plot size was 18 m^2 (6 m in length *3 m in width). In each plot, a leachate collecting device was installed in 2016. Briefly, a pit (length 1.5 m * width 0.8 m * depth 0.9 m) was dug in the middle of each plot, and soils from the pit were separated by 0–20 cm, 20–40 cm, 40–60 cm and 60–90 cm. Another hole (diameter $\varphi = 40$ cm, depth = 35 cm) was dug at the bottom of the pit to place the leachate collecting bucket together with the cover. Then, a plastic film was used to separate the pit from the bulk soil both by the surrounding and the bottom. A ring was used to connect the plastic film and the bucket, and then the plastic film above the bucket cover was removed. Quartz sand (diameter φ = 1–3 mm) was placed on the filtering mesh to act as a filter. Then, refilling the pit with soil previously dug in a reverse order, i.e., filling the soil 60–90 cm first, 40–60 cm second, 20–40 cm third and, finally, 0–20 cm. When filling 60 cm of the pit (30 cm from the surface), a knife was used to remove the plastic film attached to the surroundings, and then a protection pipe was placed on the leachate collecting line and the air-connecting line. Refilling continued as described above, and the surface was flattened when finished (Fig. S1).

2.3. Sampling and analysis of soil, leachate and plant samples

After the eggplants were removed on October 5, 2017, soil was randomly sampled in each plot every 20 cm for a total of 100 cm using a soil auger (φ = 4 cm). Soil samples from each layer were thoroughly mixed and air-dried. After removing all visible organic debris, stones and plant roots, the samples were divided into two equal parts. One part was ground to pass through a 0.25 mm sieve and digested with perchloric acid for total phosphorus (TP) (Kuo, 1996). The other part was ground to pass through a 1 mm sieve for available phosphorus (AP) analysis by extraction with sodium bicarbonate (Olsen, 1954).

Leachate samples were collected from leachate collecting buckets by vacuum pumps. The collecting system can be seen in (Fig. S1). A 3 L collecting bottle was connected to the leachate collecting line, and then the bottle was connected to a 1 L buffer bottle to prevent the leachate damaging the vacuum pump. The leachate was collected before irrigation every time. Each leachate sample was divided into three equal parts. One part was digested with potassium persulfate to determine the total phosphorus (TP) concentration (Pote et al., 2009). One part was filtered through a 0.45 μm Millipore-filter to measure total dissoluble phosphorus (TDP) using the same method as the TP analysis. The last