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Effect of bio-char application combined with straw residue mulching on soil soluble nutrient loss in sloping arable land

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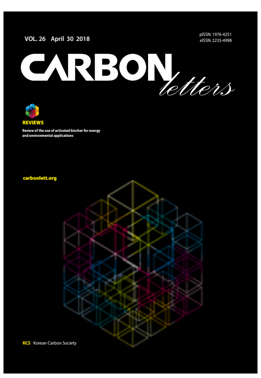

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Abstract

We assessed the effects of combining bio-char with straw residue mulching on the loss of soil soluble nutrients and citrus yield in sloping land. The two-year study showed that straw residue mulching (ST) and bio-char application combined with straw residue (ST+BC) can significantly reduce soil soluble nutrient loss when compared with the control treatment (CK). The comparative volume of the soil surface runoff after each of the treatments was as follows: CK > ST > ST + BC. Compared with the CK, the runoff volume of the ST was reduced by 13.6 % and 8.5 % in 2014 and 2015, respectively. Compared with the CK, combining bio-char with the ST application reduced the loss of soluble nitrogen and improved the soil total nitrogen content reaching a significant level in 2015. It dramatically increased the soil organic matter content over the two year period (36.3% in 2014, 50.6% in 2015) as well as the carbon/nitrogen ratio (C/N) (16.6% in 2014 and 39.3% in 2015). Straw mulching combined with bio-char showed a trend for increasing the citrus yield.

Key words: Bio-char; Soluble nutrient loss; Sloping land; Soil surface mulching

1. Introduction

In recent years bio-char has been applied to soil-related research as a new functional material [1]. Related scientific results have provided new ideas with the potential for solving problems related to material science [2], global climate change [3], soil fertility [4], carbon enrichment, and protection of the ecological environment [5]. Existing studies have shown that bio-char can change the soil bulk density, regulate the soil physical and chemical properties and improve the efficient use of soil nutrients thus increasing crop yield [6]. Raw materials to produce bio-char are mainly straw residue, wood chips and other waste organic materials [7]. The use of bio-char in agricultural production therefore not only promotes the efficient use of resources but also helps in the development of sustainable agricultural cycling and may lead to new trends in agricultural fertilization and productivity.

Loss of soil nutrients has been a key problem in agricultural production in China and in many other places in the world, particularly in sloping farmland [8,9]. Soil nutrient losses are aggravated with the increased use of chemical fertilizers leading to the occurrence of non-point source pollution. This is the result of the migration of material with the flow of surface runoff which leads to a loss of soil nutrients due to soil erosion. The consequences are a loss of available nutrients in cultivated land and reduced fertility resulting in the continued degradation of the originally barren soil which also leads to serious environmental issues. Much research has been done on the prevention and control of non-point source pollution [8-9]. Research in this field ranges from the factors influencing nutrient migration and loss from sloping land to the form and manner of the loss and leads to forecasting and forecast modeling. However, much research focuses to a large extent on theoretical description and application with widely varying results, and these studies are far from sufficient. To prevent the migration process of non-point source pollution, it is necessary to take effective measures to deal with both the soil content and the soil surface, simultaneously.

Citrus is the primary economic crop in the Danjiangkou Reservoir area, and the region is one of the main citrus producing areas of China. Approximately 20,000 hm^2 of citrus are currently planted with an annual fruit yield about 300,000 t. Farm land in the Danjiangkou Reservoir area is predominantly sloping, and agricultural non-point source pollution has caused some water quality indicators of Danjiangkou Reservoir to exceed the national water quality standard [10] especially during the rainy season, which occurs from July to October. One of the important factors leading to agricultural non-point source pollution is a lack of efficiency regarding the use of fertilizers. This coupled with the severity of soil erosion results in a reduced agricultural yield.

Crop straw is a common waste material arising from agricultural production with a very large annual output [11]. Mulching with straw can effectively reduce soil erosion caused by the impact of rain on the ground surface [12]. Bio-char, which is also produced from agricultural waste materials, is chemically and biologically very stable, due to its polycyclic aromatic structure [13]. It comprises large amounts of organic macromolecules with multi-pore structures and therefore, can easily form aggregates with soil particles improving the structure of the soil. The adsorptive property of bio-char improves the soil adsorption [14] and thus the retention of soil nutrient ions, particularly NH_4^+ [15]. Bio-char also has an impact on crop nutrient uptake, increasing the ability of plants to utilize available nutrients. Studies have shown that the use of biomass charcoal significantly increases the absorption of soil nitrogen, phosphorus and potassium in wheat [16], maize [17] and radish [18] within a certain range.

The direct source of nutrients available to plants is the soluble nutrient fraction in the soil. Loss of soil soluble nutrients will have a large impact on plant growth. Therefore, we studied the effect of combining bio-char amendment with straw mulching to control soil non-point source pollution and to decrease soil soluble nutrient loss. We believe that bio-char amendment combined with straw mulching can block or reduce the migration process of soil soluble nutrients from both the soil surface and the internal soil contents at the same time [19]. While straw mulching can reduce the impact of raindrops on the soil surface layer, bio-char has a unique adsorption capacity, which helps to reduce the nutrient loss from within the soil, and thus, both bio-char amendment and straw mulching can improve soil properties. In addition, the adsorption potential of bio-char can result in the slow release of fertilizer-derived nutrients thus lowering fertilizer nutrient losses [16], especially in cases where fertilizer is applied only once during sowing. Therefore, some of the potential multiple benefits of combining these measures include making full use of the local straw waste resources, reducing the shortage of nutrients available to crops in the late growing period, avoiding the discarding or burning of straw residue wastes and the associated pollution, reducing the agricultural production input in terms of chemical fertilizer and decreasing agricultural non-point source pollution by reducing nutrient migration and soil erosion.

Little quantitative information is available regarding the effect of bio-char amendment combined with straw residue mulching on sloping arable land. Therefore, a study was conducted in the semi-arid environment of the Xiaofuling watershed, Danjiangkou Reservoir area, China, where citrus is farmed in sandy loam soil on sloping land. The aim was to evaluate the effect of bio-char amendment combined with rice straw mulching on the loss of soil soluble nutrients in sloping orchards as well as assessing the effects on the soil nutrients content and fruit yield.

2 Materials and methods

2.1 Site description

This study was conducted in 2014-2015 in the Xiaofuling watershed of the Danjiangkou Reservoir area (32°36 " –33°48 " N, 110°59 " –111°49 " E) located in central China (Fig.1). The research area is characterized by a typical subtropical monsoon climate with a mean air temperature of 2.4℃ in January and 28.4℃ in July. Local soil type is sandy loam soil. Mean annual

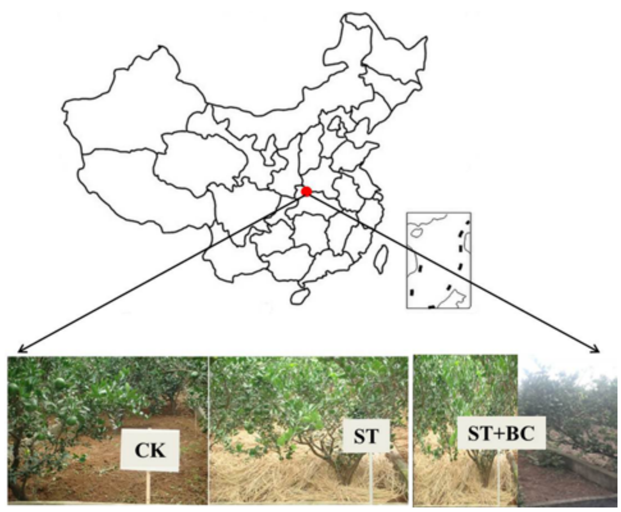

Fig. 1. Experimental site

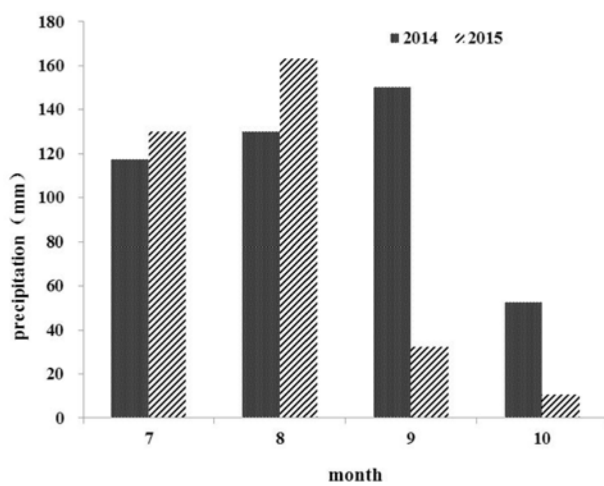

Fig. 2. Rainfall during the monsoon

Table 1. The basic chemical properties of the tested bio-char (g kg^{-1})

Total N	Total P	Total K	C	Ca	Mg	Zn	pH
2.2	1.4	18.8	798	2.8	1.7	0.07	9.48

precipitation for the last 10 years is approximately 813 mm, 84 % of which falls between July and October, while the equivalent value for 2014 and 2015 was 49% and 47%, respectively, lower than the 10-year average (Fig. 2).

2.2 Experimental design

The experiment was designed as a randomized complete block with three treatments in triplicate. The three treatments included the following: control treatment without any cover (CK), rice straw mulching treatment (ST, cover 4500 kg hm^{-2} rice straw) and straw residue mulching combined with bio-char treatment (ST+BC, cover 4500 kg hm^{-2} rice straw after 9 t hm^{-2} bio-char was combined with the soil). The bio-char was made from bamboo produced by Shanghai Seek Biological Technology Co., Ltd. The basic chemical properties of the tested bio-char are shown in Table 1. Each plot was 40 m^2 in size (4 m×10 m) and established at the same high level with an average slope of 19.5°. Each runoff plot was separated by concrete borders. There were 10 citrus plants (cultivar named ‘Weizhang’) in each plot. The fertilizers urea (0.8 kg N/plant), superphosphate (0.2 kg P_2O_5/plant) and KCl (0.2 kg K_2O/plant) were added annually during the blooming stage to each treatment by spot application, and any other management was identical for all treatments. Branches of the citrus trees were removed from the plots after trimming.

2.3 Sampling and analysis

Mixed soil samples from 5 points in each plot were taken using a soil borer from the soil surface layer (0-20 cm) collected 3 times from January 2014 to December 2015 resulting in a total of 90 samples. After removing animal and plant residues and pebbles, soil samples were air dried and put through a 100 or 200 mesh sieve for further analysis. Total soil organic matter (SOM) was measured by the $K_2Cr_2O_7$ oxidation method; total N was determined by the Kjeldhal method; available N was measured by the Alkaline diffusion method; available phosphorus (P) was determined by the Olsen method; dissolved C was measured by a TOC analyzer, and pH (1:10, soil to water rate) was determined with a pH meter [20].

The daily rainfall was recorded with a standard recording rain gauge (100 m^3), which was situated at the side of the experimental field. The runoff volume for each experimental plot was monitored after each runoff-producing rainfall. It was collected by a 50 L plastic bucket which is placed in the gauge. To analyze the samples, the collected runoff was thoroughly mixed and divided into 500 mL stock composite samples (or the sample kept in its entirety if under 500 mL) and stored at 4℃ until the investigation. The samples were filtered using Whatman no. 1 filter paper with a pore size 0.45 m and tested for dissolved C, N and P.

At the time of the fruit harvest, the citrus fruits were harvested gradually when they were ripe. The yield per plot was obtained by weighing the harvested fruit. A random sample of 25 fruits from each direction in each plot was collected to determine the average fruit weight. In addition, the index of the fruit shape from each experimental plot was measured by measuring the equatorial diameter of a chosen fruit with the help of a Vernier caliper. Using a standard juicer, 25 fruits were juiced. The mixed juice was investigated for vitamin C (Vc), soluble sugar, and organic acid soluble solids using the 2,4-Dintrophenylhydrazine, Anthrone, Neutralization test method and Soluble solids content analyzer respectively.

2.4. Statistical analyses

Experimental data were analyzed using the SPSS 16.0 software package and Microsoft Office Excel 2010. One-way analysis of variance (ANOVA) was carried out to determine the differences between the measured parameters for different treatments. Least significant difference (LSD) at P = 0.05 was used to elucidate any significant differences.

3. Results and Discussion

3.1 Effects of the different treatments on the runoff volume

The runoff volumes of each treatment are shown in Fig. 3, and the trends (CK> ST >ST+BC) were found to be the same

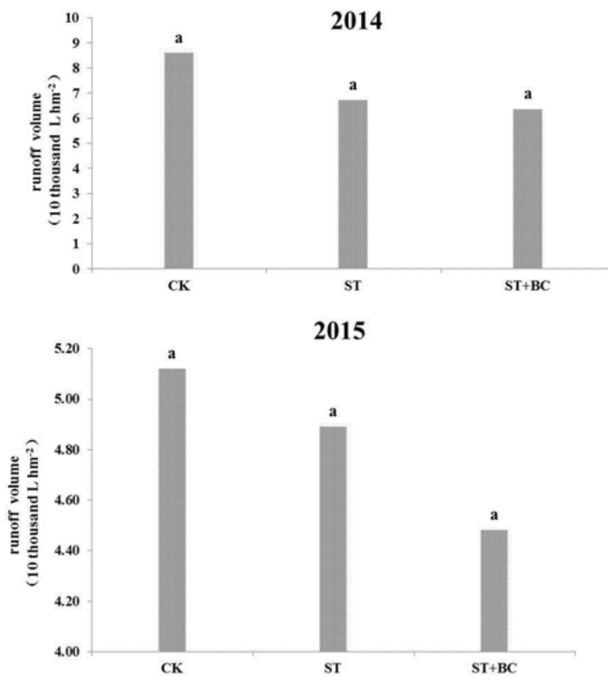

Fig. 3. Runoff volumes under the different treatments in the citrus orchard

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in the results from both 2014 and 2015. The runoff volume of CK, ST & ST+BC reached 8.59, 6.70 and 6.36 myrialiter per hectare, respectively, in 2014 and 5.12, 4.89 and 4.48 myrialiter per hectare in 2015, respectively. Compared with CK, mulching treatments showed a trend of decreasing the runoff volume by 13.6% and 8.5%, respectively, in 2014 and 2015, but the difference was not significant. A mulch layer can resist soil surface runoff flushing, reduce the impact of raindrops on the soil surface and minimize the formation of a soil surface crust thus prolonging the flow time and increasing soil infiltration. Wang *et al*., [9] reported in their study that straw mulching decreased soil surface runoff volume by 30.47% compared with CK.

3.2 Effect of the different treatments on the soluble nutrient loss

The following bar chart (Fig.4) shows carbon, nitrogen and phosphorus losses due to the runoff among the different treatments.

Compared with CK, ST and ST+BC showed a trend for decreasing the soil surface runoff volume while the trends for nutrient losses were consistent in both years (204 and 2015) of the study. Carbon losses were much higher than those of nitrogen and phosphorus. Among the three treatments, ST lost more soluble C due to runoff than CK and ST+BC. Mulching treatments showed more carbon losses, particularly in 2015, but the difference was not significant.

Nitrogen losses from mulching treatments were marginally higher than the no mulching treatment, and soluble nitrogen losses with ST were more than with ST+BC. Phosphorus losses followed this trend: CK > ST > ST + BC. The phosphorus losses following no mulching treatment were significantly higher than those following the mulching treatment. The differences

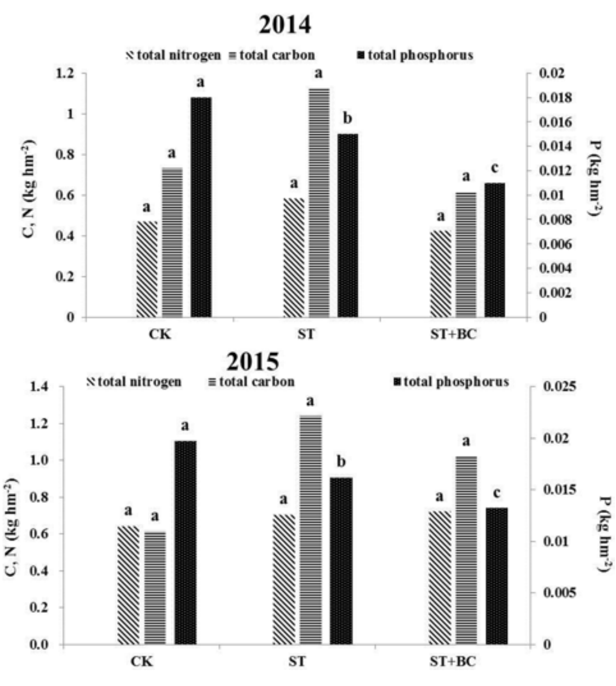

Fig. 4. Soluble nutrient losses under the different treatments

between the ST and ST+BC were not significant. These results imply that both the ST and ST+BC can reduce phosphorus lost with runoff, and the ST+BC is bette r than the ST in controlling soil phosphorus losses.

The reason for the high nutrient losses not being reduced under the mulching treatments may be the addition of nutrients from the mulching itself acting as an outside source. Zhao *et al*. [21] found carbon release from soil surface straw mulching after 150 days of decomposition to be as high as 50%. In this study, out sourced carbon input in the ST and ST+BC is much higher than that of the CK. Straw decomposition would have released much soluble carbon, which is very easily removed by soil surface runoff [19], while straw mulching combined with bio-char decreased this trend because of the absorption capabilities of the bio-char [5].

Zhao *et al*. [21] found that 24 % of the nitrogen content of straw could be released after 150 days of decomposition post soil surface mulching. Nitrogen is water soluble and easily removed by runoff on sloping land. However, when straw mulching is combined with the bio-char application, the soil benefits from the absorption ability of the bio-char, and thus, nitrogen, both from straw release and soil decomposition, can be retained in the soil. The soluble phosphorus content is very low in both the straw and bio-char treatment. Soil surface mulching measures reduced the soil surface runoff to some extent, and by this means, mulching treatments significantly decreased the soluble phosphorus losses.

Faucette *et al*. [22] found that nutrient losses from different compost treatments under wood mulching varied significantly due to the variation in the availability of nutrients in the different composts. In our study, both the rice straw and bio-char contained high levels of soluble nutrients; therefore, the nutrients in the ST and ST+BC treatments would have been more available to runoff than the equivalent in CK. Moreover, both the ST and ST+BC treatments can enhance the soil nutrient content by a priming effect; this might be another reason why mulching treatments show a trend for a greater runoff-sourced nutrient loss.

3.3 Effect of the different treatments on the soil carbon and nitrogen

The carbon and nitrogen content of the soil surface layer (0-20cm) is shown in Table 2. We found in the 0-20 cm layer that the soil total nitrogen, soil organic matter, available nitrogen content and C/N ratio from the samples with mulching were significantly higher than that of the CK, but there were no significant differences between the ST and ST+BC treatments. The soil organic matter of the ST+BC was 14.62 and 22.02 gkg^{-1}; total nitrogen was 0.967 and 1.167 $g\ kg^{-1}$, and available nitrogen was 56.35 and 53.20 $mg\ kg^{-1}$ in 2014 and 2015, respectively, which were higher than those of the other treatments. The soil organic matter of the ST+BC, in particularly, increased significantly compared to that of the CK by 36.3 % in the first year and further increased in the second year to 50.6 %. The nitrogen content of the soil showed no significant difference among the three treatments in 2014, while when compared with the CK and ST, this number was significantly increased, by 28.9 % in the ST+BC treatment in 2015.

The maximum soil surface available nitrogen content was ob-

Table 2. Soil C and N contents and pH under the different treatments

Year	Treatment	TN g kg-1	SOM g kg-1	Available nitrogen g kg-1	C/N	pH
2014	CK	0.815a	10.723b	49.35a	13.16b	7.1a
	ST	0.859a	13.378a	52.15a	15.57a	7.0a
	ST+BC	0.967a	14.620a	56.35a	15.12a	6.9a
2015	CK	0.905b	10.654b	44.10a	11.77c	7.2a
	ST	0.871b	12.120b	51.10a	13.91b	7.1a
	ST+BC	1.167a	22.015a	53.20a	18.87a	7.2a

Note: Values followed by different letters within a column are significantly different ($P < 0.05$), same hereinafter.

Table 3. Correlations between the runoff volume and nutrient losses

		Runoff volume	TN	TP	TC
2014	Runoff volume	1	-0.683	0.896**	-0.668
	TN		1	-0.288	0.9998**
	TP			1	-0.268
	TC				1
2015	Runoff volume	1	-0.942**	0.977**	-0.668
	TN		1	-0.992**	0.879**
	TP			1	-0.811
	TC				1

Note: **. Correlations were very significant ($p<0.01$).

served in the ST+BC in both 2014 and 2015 (56.35 and 53.20 mg kg^{-1}), and the trend for the available nitrogen content among the three treatments was CK < ST < ST+BC. However, this difference was not significant. Compared with CK, the C/N in the soil surface layer with the treatments ST and ST+BC was increased significantly by 18.3 % and 14.9 % in 2014 and 18.2 % and 60.3 % in 2015, respectively. This is in agreement with the findings of Liu *et al*. [17], in which both straw mulching and bio-char application could improve the soil nutrient availability, promote nutrient absorption and increase the activity of soil microorganisms. No significant effect of bio-char was found on soil pH.

3.4 Correlation between the runoff volume and the runoff nutrient content

The correlation between the soil surface runoff volume and the runoff nutrient loss is shown in Table 3. The results show that carbon loss with runoff and soluble nitrogen loss are significantly related as is the runoff volume with the soluble phosphorous loss. However, no positive significant relationship was found between the runoff volume and the soluble carbon or nitrogen losses in either 2014 or 2015.

Former research has shown that soil nutrient losses positively correlated with the runoff volume. In our study, soluble P losses showed a positive correlation with the runoff volume while the C and N losses were less and in some cases, even negatively, correlated with the runoff volume. This may be related to the time of fertilizer application. In our study, fertilizer was applied in March, which is the dry season, so that although runoff may be lower, it may contain large amounts of soluble nutrients. By the time the rainy season comes, nutrients might have been absorbed or immobilized, resulting in large runoff volumes, but lower soluble nutrient loss. However, field experimental conditions are very complex，and factors such as the nature of precipitation and land formation can also affect soil nutrient losses. Walton *et al*. [8] investigated sloping land with a slope of less than 2 % and found that soluble nutrient losses have no significant relationship with the rainfall intensity but are affected by the initial time taken to produce the runoff. Flanagan *et al*. [23] found no statistical differences between soluble nutrient losses caused by different types of rainfall, whereas Huang *et al*. [24] found that soluble nutrient losses were positively related to rainfall intensity.

Some scholars believe that there is a critical slope related to soil nutrient losses in sloping land in the range of 15°~ 20°. When the slope is less than the critical value, the nutrient losses increase with increasing slope; and when the slope is greater than the critical value, nutrient losses decrease with the increasing slope [25].

Table 4. Citrus fruit yield and external quality

Year	Treatment	Yield/ t hm^{-2}	SFW/ g	IFS
2014	CK	56.566 a	121.41 a	0.83 a
	ST	60.606 a	108.52 a	0.83 a
	ST+BC	67.677 a	114.32 a	0.85 a
2015	CK	5.839 ab	148.14 b	0.91 b
	ST	3.952 b	166.07 a	0.92 a
	ST+BC	7.174 a	135.80 c	0.95 a

Table 5. Citrus fruit content quality

Year	Treatment	Vc g kg^{-1}	soluble sugar %	organic acid %	sugar-acid ratio	soluble solids %
2014	CK	0.380a	8.90 a	0.50 b	18.50 a	10.64 b
	ST	0.377 a	8.60 a	0.50 c	18.41 a	12.43 a
	ST+BC	0.351 b	8.66 a	0.51 a	17.02 b	9.88 c
2015	CK	0.319 ab	11.15 a	0.67 a	17.81 b	11.47 a
	ST	0.346 a	12.41 a	0.56 b	22.29 a	11.39 a
	ST+BC	0.290 b	11.93 a	0.55 b	21.73 ab	10.67 a

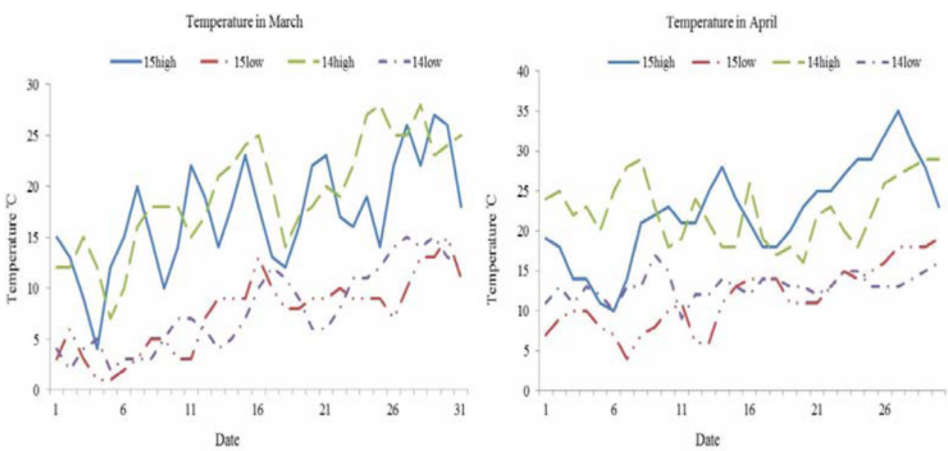

Fig. 5. Temperature during the citrus blooming period

3.5 Effect of the different treatments on the citrus fruit yield and quality

Regarding the cultivation of fruit trees, attention needs to be given not only to the yield productivity but also to the quality of the fruit. Citrus yield and fruit quality following the treatments are shown in Tables 4 and 5. Because of the extreme cold weather experienced in 2015 during the citrus blooming period (March to April), the citrus yield decreased dramatically in 2015 (Fig.5); however, the index of fruit shape (IFS) in 2015 was higher than that in 2014. The citrus yield and IFS peaked with the ST+BC treatment in both 2014 and 2015. In the fruit market, the most intuitive evaluation of citrus includes the single fruit weight (SFW) and the index of fruit shape (IFS). Compared among the different treatments, the SFW and IFS had no significant differences among the treatments in 2014, while in 2015, the treatment with ST+BC significantly increased the citrus yield and improved the fruit shape. The supply of nutrients in the soil influences the growth of trees and thus, also the yield and quality of the fruit. Akhtar *et al*. [26] found that the tomato yield could be significantly increased by the application of bio-char. In our study, the trend for the citrus yield increased with the application of bio-char combined with mulch, but the differences were not significant.

When compared with the CK, the mulching treatments did not appear to have any significant effect on the citrus soluble sugar and had no clear trend for the effect on the Vc, organic acid, sugar-acid ratio and soluble solids. When compared among the mulching treatments, the Vc content, sugar-acid ratio and soluble solids of the ST were higher than those with the ST+BC treatment.

Akhtar *et al*. [26] found that bio-char application could not significantly increase the soluble sugar and Vc content which is consistent with the results in our study for both 2014 and 2015, which is also consistent with the results of Liu *et al*. [10]. However, one should be aware that the Vc levels in fruits largely depend on various factors including the cultivar, plant nutrition, production practice and degree of maturity [27].

4 Conclusion

Both straw mulching and straw mulching combined with biochar application showed a trend for decreasing the soil surface runoff volume as well as the soluble nitrogen loss. This trend was more obvious when bio-char was combined, especially during the year of higher rainfall. Straw mulching combined with bio-char could significantly decrease the soluble phosphorus loss. Losses of soluble nutrients are largely influenced by the timing of the fertilizer application and the precipitation conditions during the early period of the fertilizer amendment. Biochar application can dramatically improve the soil total nitrogen, soil organic matter and C/N ratio. Straw mulching combined with bio-char showed a trend for increasing the citrus yield. The effect of the bio-char application on the citrus fruit quality is still not clear and warrants further study.

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