Performance of Grass Filter Strip in Copper and Zinc Removal in Surface and Subsurface Runoff

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Abstract. Three filter strips were conducted on self-designed soil bins. Taking a filter strip with no vegetation as contrast, the effectiveness of vegetation and soil conditions on heavy metals (including copper and zinc) removal efficiencies were investigated by simulated runoff experiment. The results showed that the adsorbed state is the main existing form of heavy metal. For surface runoff, most of total copper and total zinc are trapped in first 4m and it is ineffective to increase the distance beyond 4m for removal. Vegetation has no significant effect on total copper and total zinc removal, while the soil with higher content of organic matter is contributing to total Zn interception. For subsurface runoff, the removal efficiencies of total copper and total zinc can reach to above 95.38% and both vegetation and soil conditions have no significant effects. Vegetation is contributing to copper ion and zinc ion removal significantly. Soil condition is only a significant factor to zinc ion, with higher content of organic matter as a contributing factor.

1 Introduction

Even Intensive agriculture has sustained the world development, but some agricultural activities are contributing to the environmental health decreases at local, regional, and global scales. In China, the contaminants discharged in key river basins from agriculture are much more than from industry [1]. The excess sediment, nutrient and heavy metals from agricultural runoff have been a major cause to water quality deterioration.

Vegetative filter strip here is defined as a band of soil planted with permanent vegetation, and when the cropland runoff flows across the area, it undergoes a decrease of pollutant concentration and volume. Over the past decades, numerous studies have shown that it is a proposing way to attenuate sediment and nutrient in cropland run off [2-6].

Vegetative filter strip can disperse current and reduce the velocity of runoff and promote sedimentation, infiltration and adsorption. Vegetation plays an important role, such as soil conservation, biological utilization, improving soil permeability. The vegetation types used in studies include perennial grasses [7-11], shrubs [12-14], forests [15,16] and combinations of those above.

Compared to forest and shrub, grass filer strip is still economical alternative to reduce non-point source pollutants，and particularly those native grasses with tall, erect and stiff stems and strong root systems, is highly valued for removing particulate contaminants. Fescue is a common choice to construct grass filter strip, which is a kind of tufted grasses with strong fibrous root system, and widely used for buffer zones. In a field experiment, Daniels found that the fescue filter strip reduced runoff load by 50～80%, TSS by 80%, TP by 50% and retained NH4+-N by 20～50% [17]. Under simulated rainfall conditions, Magette found that the Kentucky-31 fescue filter strips were effective to remove nutrient in runoff [7]. Another study compared three practices, and reported that the fescue strip with switchgrass barrier was the most effective to reduce losses of organic N, NO_3^--N, NH_4^+-N, PP and PO_4^{3-}-P [8]. These studies have shown the effect of tall fescue filter strip on contaminants removal successfully.

Besides vegetation, soil condition is also an important factor to the effect of filter strip. The component, porosity, and texture of soil are usually positively correlated with precipitation volume and removal efficiency of pollutant.

Heavy metal pollution is long lasting, irreversible and it is hard to give rid of its influence once it is introduced into environment. It can harm human health and ecosystem safety through food chain. However, the studies on heavy metal attenuation by vegetative filter strips have been fewer.

The objectives of this study were : (i) to compare copper (Cu) and zinc (Zn) removal efficiencies by contrast filter strip, tall fescue filter strips with different soils,(ii) to estimate the effects of vegetation and soil on total heavy metals and heavy metal ions removal in surface runoff and subsurface runoff.

2 Materials and methods

2.1 Construction of experimental system

Experimental system is consisted of PE bucket and soil bin system. The volume of PE bucket is 800L, and water is controlled by flow meter. Soil bin system is consisted of drainage channel and soil bin. Drainage channel is 7.5×10^{-2} m^3 (Length 0.3m * width 0.5m * high 0.5m), while soil bin is 1.5 m^3 (long 6.0m * width 0.5m * high 0.5m). Water from PE bucket flows firstly into the drainage channel, and then enters into soil bin by horizontal overflow. There are three surface holes along the bin of 2m, 4m and 6m (No.01, 03 and 05), and three bottom holes (No.02, 04 and 06) corresponding to surface holes vertically. The soil bin is placed on the bracket with adjustable slope, and the structure is shown in Figure 1.

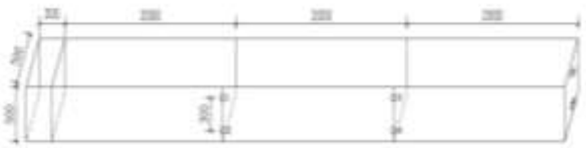

Figure 1. Sketch Map of Soil Bin System (unit: mm).

Soil bin is filled with soil of 0.35m depth. There are three filter strips constructed on three soil bins. The set is as follows: C is a contrast filter strip with no plant in it, and 1# soil is filled in. A is a tall fescue filter strip with 1# soil filled in. The tall fescue grows with coverage 90%, average root length of 35cm, average tissue height aboveground of 42cm, fresh weight of 4.11 kg m^{-2}, dry weight of 0.721 kgm^{-2}. B is also a tall fescue filter strip with 2# soil filled in. The tall fescue grows with coverage around 90%, average root length of 36cm, average tissue height aboveground of 40cm, fresh weight of 4.76 kg m^{-2}, dry weight of 0.913 kg m^{-2}. The main physical and chemical properties of 1# and 2# soil are listed in Table 1. According to the soil mechanical composition data and international standard of soil texture classification, 1# soil is specified as silt loam, while 2# soil is specified as clay loam [18].

Table 1. The main physical and chemical properties of the tested soil.

Soil No.	organic matter	Cu	Zn	CEC	particle composition%		
	g Kg^{-1}	mg Kg^{-1}		cmol $^{+}Kg^{-1}$	sand	powder	clay
1#	5.64	25.1	156	3.41	70.96	26.00	3.04
2#	18.25	18.2	59.0	12.5	61.83	20.76	17.41

Note: The unit of CED is $cmol^{+}$ Kg^{-1}, which is positive charge per kilogram.

2.2 Experimental scheme

Experimental devices are located on the bank of Kunyu River, near Yu Yuan Tan park, in Beijing, China. Simulated runoff experiments are applied. Experimental water is extracted from river into bucket (800L), and soil particles and concentrated solutions of heavy metal (Cu, Zn) are accurately added into bucket according to the experimental design, which is to simulate the sand and heavy metal in cropland runoff.

Grouped comparison is applied. Vegetation effect is investigated by contrast filter strip versus tall fescue filter strip(C versus A).Soil condition effect is investigated by soil 1# versus soil 2#(A versus B).

Since the start of the simulation runoff, system inlet water samples from outlet of bucket are collected by every 10-15 minutes. Surface runoff samples from surface holes along the bin of 2m, 4m and 6m are collected. Subsurface runoff samples from bottom holes along the bin of 2m, 4m, 6m are also collected. The concentrations of heavy metals are determined immediately after collection.

Heavy metal determined in this study is divided into total amount of heavy metals and heavy metal ions. The concentration of total amount was determined by total water sample acid digestion. Briefly, a volume of 15mL of total water sample was weighed. About 1.5mL concentrated HNO_3 was added to sample and the sample was heated to concentrate into 2-5ml.Then 1.5ml HNO_3 and 0.2 mL H_2O_2 were added into that concentrated solution. Then it continues to concentrate into 1ml. Lastly, ionized water is added to sample until the volume to 25mL. Determination of heavy metal ions is directly to use the water sample that is filtered by 0.45μm membrane. All the heavy metal concentrations determination is completed by ICP-MS(Perkin-Elmer, USA).HNO_3 and H_2O_2 used in experiment are guarantee reagent. Parallel sample determination should be done for ensure the precision of the experiment. The relative standard deviations of heavy metals were less than 5%.

3 Results and analysis

3.1 Analysis of interception characteristics of heavy metals in surface runoff

Heavy metal existing in runoff water and sediment is generally divided into particulate and dissolved fractions by filter through a 0.45 μ m membrane. Heavy metals ion may be combined with the active groups of soil particles by adsorption, and may get into water by desorption. Heavy metal ion exists in the balance of adsorption and desorption. Cu and Zn are chosen as target pollutants and their interception features are investigated by surface runoff and subsurface runoff.

Heavy metal determination in surface runoff is total amount determination, including adsorbed heavy metals combined with suspended matter, as well as heavy metal ion with reactive activity that dissolved in water. Total Cu removal efficiencies in surface runoff are shown in Figure 2.

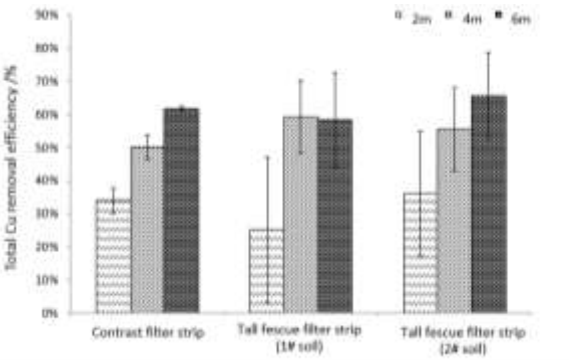

Figure 2. Total Cu removal efficiencies in surface runoff along 2m, 4m, and 6m of strip.

Total Cu removal efficiencies of contrast filter strip with 2m, 4m and 6m are 33.89%, 50.13% and 61.61% successively. Total Cu removal efficiencies of tall fescue filter (1# soil) are 25.09%, 59.19% and 58.30% successively. Total Cu removal efficiencies of tall fescue filter (2# soil) are 36.00%, 55.47% and 65.42%. The result is shown that the total Cu removal efficiencies of all filter strips have the trend of increasing with the filter width increasing. Comparing the total Cu removal efficiencies along 2m, 4m, and 6m of filter strip, that of 4m is significantly higher than that of 2m, and the removal is slowing down with width increasing from 4m to 6m.Therefore, 0-4m is considered to be the main strip width of Cu interception.

Adopting the method of spss17.0 one-way analysis of variance to compare the Cu removal efficiency of 6m filter strip, it is found that there is no significant difference(p=0.753) between contrast filter strip and tall fescue filter strip (A with 1# soil). And there is no significant difference(p=0.562) between tall fescue filter strip with 1# soil (A) and tall fescue filter strip with 2# soil (B). Therefore, the vegetation condition and soil condition are not significant factors to Cu removal efficiency.

Total Zn removal efficiencies in surface runoff along 2m, 4m, and 6m are shown in Figure 3. Total Zn removal efficiencies of contrast filter strip with 2m, 4m and 6m are24.78%, 36.29% and35.97% successively. Total Zn removal efficiencies of tall fescue filter (1# soil) are 35.28%, 30.78% and 31.48% successively. Total Zn removal efficiencies of tall fescue filter (2# soil) are 24.21%, 44.35% and 51.71% successively.

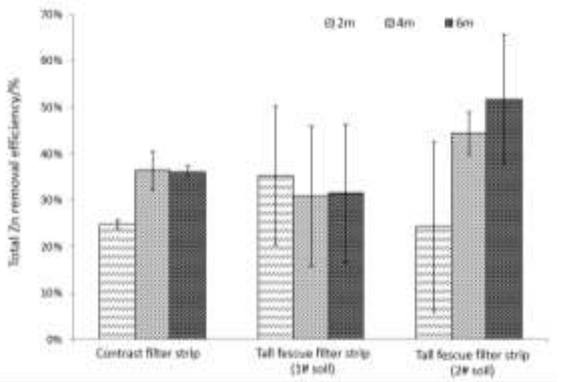

Figure 3. Total Zn removal efficiencies in surface runoff along 2m, 4m, and 6m of strip.

The result is shown that the total Zn removal efficiencies of contrast filter strip and tall fescue filter strip (with 2# soil) have the trend of increasing with the filter width increasing. But the tall fescue filter strip with 1# soil does have the trend. It is same as total Cu interception that 0-4m is considered to be the main range of strip width for interception.

Adopting the method of spss17.0 one-way analysis of variance to compare the Zn removal efficiency of 6m filter strip, it is found that there is no significant difference (p=0.167) between contrast filter strip and tall fescue filter strip (A with 1# soil). But the removal of tall fescue filter strip with 2# soil is significantly better than tall fescue filter strip with 1# soil ($p<0.05$). It can be drawn that vegetation condition is not a significant factor to total Zn removal efficiency, but soil condition is a significant factor. The soil with higher organic matter content has the higher removal efficiency. In addition, Zn content of 2# soil is 59 mg Kg-1, which is lower than that of 1# soil (156 mg Kg^{-1}). The soil owning lower Zn content has the greater adsorption capacity, which might be one of the reasons that affect the removal efficiency of filter strip.

The total content of heavy metals in surface runoff is determined, which includes adsorbed heavy metals and heavy metal ion. The inflow concentration of total Cu is 68.76～99.23μg L^{-1} and that of total Zn is 267.95～496.00μg L^{-1}.The inflow concentration of Cu^{2+} is 4.310～9.737μg L^{-1} and that of Zn^{2+} is 24.885～81.901μg L^{-1}. By comparison of Cu and Zn, it is found that ion component has smaller proportion in total content, with Cu^{2+} accounting for 6.27%～9.81% and Zn^{2+}accounting for 9.29%～16.51%. Therefore, the heavy metal adsorbed with sediment is the main existence in inflow water.

When water flows through the filter system consisting of soil and vegetation, the pollutants get preliminarily intercepted by physical and chemical processes like deposition, filtration, adsorption within a short retention time. And the intercepted pollutants will be transformed further by plant absorption, microbial metabolism and chemical reaction [19-20].

The vegetation is a necessary element of filter strip system, which can block the surface runoff and reduce the speed of runoff. So vegetation can promote particles deposition and the adsorbed pollutant retention. The retention time will be extended, which promotes the interception between pollutants and adsorption sites [21-22]. In addition, the plant tissue can contact with runoff, which can produce adsorption to heavy metal. The growth of vegetation can increase the content of organic matter in soil, which is conductive to the adsorption reaction.

Comparing the effects of soil conditions, it can be concluded that Zn in tall fescue filter strip (2# soil) is significantly higher than tall fescue filter strip (1# soil) , while the soil has no significant effect on removal efficiency of Cu. The organic matter content of 1# soil was 5.86～6.90 g Kg^{-1} and that of 2# soil is 11.62～13.92 g Kg^{-1}. The content of organic matter of soil 2# is significantly higher than that of soil 1# ($p<0.01$).Except organic matters, the caption exchange capacity (CEC) and clay proportion of 2# soil are also higher than those of soil 1#. And the condition mentioned above is conductive to the adsorption reaction [23-24].

3.2 Analysis of interception characteristics of heavy metals in subsurface runoff

The grass filter strip system constructed between pollution source and receiving water can change the hydraulic characteristics of surface runoff. Vegetation barrier and soil percolation can slow surface runoff, and the hydraulic retention time is extended. All the above can promote surface runoff to infiltrate. Therefore, soil percolation is an important way for filter strip to intercept pollutants. In this study, seepage water samples are collected from bottom holes, and the interception effect of heavy metal during seepage through 0.35m of soil layer is studied.

The interception effect of total amount heavy metal and heavy metal ion are investigated in this section. The removal efficiencies of total Cu and Cu^{2+} in water of 6m outlet is shown in Figure 4. Total Cu removal efficiencies of contrast filter strip, tall fescue filter strip (1# soil) and tall fescue filter strip (2# soil) are 96.16%, 96.50% and 95.62% successively. And those of Cu^{2+} are 56.31%, 76.23% and 74.55% successively. Adopting the spss17.0 one-way analysis of variance to compare the total Cu removal efficiencies, it can be drawn that there is no significant difference (p=0.825) between contrast filter strip and tall fescue filter strip. But Cu^{2+} removal efficiency of tall fescue filter strip is significantly higher than contrast filter strip ($p<0.05$. There is no significant difference of total Cu and Cu^{2+} removal efficiencies in both tall fescue filter strips (p=0.845 and p=0.727).

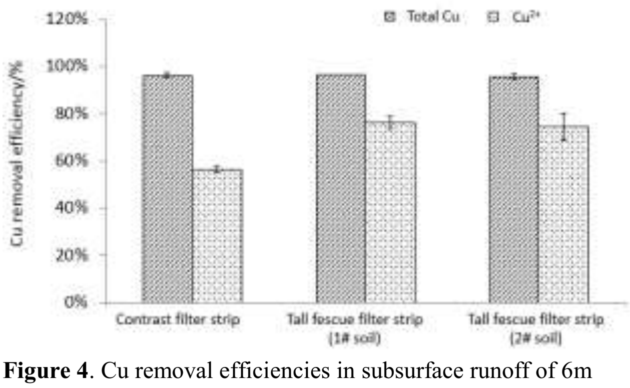

Figure 4. Cu removal efficiencies in subsurface runoff of 6m strip.

The removal efficiencies of total Zn and Zn^{2+} are shown in Figure 5. Total Zn removal efficiencies of contrast filter strip, tall fescue filter strip (1# soil) and tall fescue filter strip (2# soil) are 99.70%, 96.57% and 95.38% successively. And the removal efficiencies of $Zn^{2+}$are 62.68%, 81.43% and 86.42% successively.

Adopting the spss17.0 one-way analysis of variance to compare the total Zn removal efficiencies, it can be drawn that there is no significant difference (p=0.869) between contrast filter strip and tall fescue filter strip. But Zn^{2+} removal efficiency of tall fescue filter strip is significantly higher than contrast filter strip ($p<0.05$). There is no significant difference of total Zn removal efficiency in both tall fescue filter strip (p=902), but Zn^{2+} removal efficiency of strip with 2# soil is significantly higher than that of strip with 1# soil ($p<0.05$).

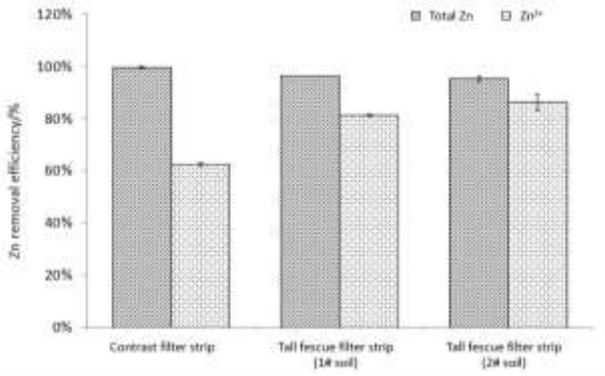

Figure 5. Zn removal efficiencies in subsurface runoff of 6m strip.

Based on the analysis above, it can be drawn that the interception of Cu and Zn in 0.35m of soil layer are similar. For the total amount of heavy metal, the vegetation condition and soil condition are not significant factors. For heavy metal ion, vegetation condition is an significant factor, and the existence of vegetation is advantageous to the interception of Cu and Zn ions. The soil condition is a significant factor to Zn^{2+}, and 2# soil is more advantageous to the interception of Zn^{2+}.

Total heavy metal includes heavy metal ion and the absorbed heavy metal, and the absorbed one takes on a greater proportion. During the process of water infiltration, most of suspended matters can not seepage through the soil pore, and has been intercepted at the soil layer. Therefore, there is no significant difference for total heavy metal interception in different conditions of vegetation and soil. And the total heavy metal removal efficiency can reach to above 95.38%, which is significantly higher than corresponding ion. The interception process of heavy metal ions through the soil infiltration is more complicated, which including the physical and chemical processes like soil adsorption and desorption, vegetation adsorption and microbial metabolism [25-28]. But within a short term of hydraulic retention, the adsorption and desorption should be a more important process. The water electrical conductivity of surface runoff is around 585.5～655.5μs cm^{-1}, while the seepage water electrical conductivity is 424.0～526.5 μ s cm^{-1}, and there is no significant difference (p=0.856) between different vegetation and soil conditions. The change of water electrical conductivity shows the process mentioned above are less, such as mineralization of organic matter, biodegradation and caption exchange, that can increase the number of ions in solution. While the adsorption that can decrease the ion number may be the main process to reduce electrical conductivity, which is also verify that adsorption effect is the primary mechanism in penetration process.

4 Conclusion

(1) The interception characteristics of total heavy metal are investigated in surface runoff. Adsorbed state is the main existence form of heavy metal in surface runoff, and their interceptions are occurred mainly in the length of 0-4m. The removal is slowing down with length increasing from 4m to 6m.The conditions of vegetation and soil have different effects on total Cu and total Zn removal. Vegetation has no significant effect on both heavy metals removal, but the soil with higher content of organic matter is contributing to the interception of total Zn.

(2) The interception characteristics of total heavy metal and heavy metal ions are investigated in subsurface runoff. By the seepage of 0.35m of soil layer, the removal efficiencies of total Cu and total Zn can reach to above 95.38%, which is significantly higher than corresponding ions, and both vegetation and soil conditions have no significant effects. For ions, vegetation is contributing to Cu^{2+} and Zn^{2+} removal significantly. Soil condition is only a significant factor to Zn^{2+}, with higher content of organic matter as contributing factor.

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