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Vegetated ridge and sandbag may not reduce soil erosion and loss of carbon and nutrients from upland fields

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ABSTRACT

Though construction of vegetated ridge (VR) and placement of sandbag (SB) across the slope of upland fields are believed to be effective in reducing soil erosion and nutrient loss, relevant data are lacking to confirm such expectations. In this study, the effects of VR and SB on loss of soils, carbon (C), nitrogen (N), and phosphorus (P) (CNP) were
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lack of beneficial effects of VR and SB on soil and nutrient loss. As VR and SB are easy to be implemented and cost-effective, however, further study is necessary to correct the flaws of VR and SB found in this study.

KEY WORDS: Land management non-point source pollution nutrient loss rainfall soil loss

1. Introduction

Soil erosion by water is a common environmental problem in intensive agricultural systems due to frequent disturbance of soils for cultivation (Biddoccu, Opsi, and Cavallo 2014; Nearing et al. 2017). Soil erosion degrades soil quality and fertility through the loss of soil particles enriched with organic matter and nutrients, and thus hampers soil productivity (den Biggelaar et al. 2004). In addition, carbon (C), nitrogen (N), and phosphorus (P) (CNP) that are transported in particulate forms with soil particles or in the dissolved forms to water body contaminate water, causing eutrophication and disturbance of aquatic ecosystems (Issaka and Ashraf 2017). It is also highlighted that soil erosion plays a significant role in the biogeochemical cycle of C, and thus C loss by soil erosion may deteriorate soil C sequestration capacity (Ran et al. 2018). Therefore, to minimize soil erosion and CNP loss via surface runoff, best management practices (BMPs) have been suggested (Morgan 2005; Xiong, Sun, and Chen 2018). Particularly, soil surface cover with crop residue (Prosdocimi, Tarolli, and Cerdà 2016), vegetative filter strip (Lobo and Bonilla 2017), and contour ridge cultivation (Liu et al. 2015) are the most common practices and thus these BMPs have been well studied.

In many countries including UK (Kay, Edwards, and Foulger 2009; Kay et al. 2012), USA (Whitney et al. 2012), and South Korea (Choi et al. 2017), such agricultural BMPs to
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water in furrows, thereby, increasing infiltration and reducing soil erosion, their effects on soil erosion and CNP loss have rarely been documented. Though a few studies are available for VR (Kim et al. 2012; Kim and Kim 2015), no experimental data is available for SB. Besides, in the studies for VR (Kim et al. 2012; Kim and Kim 2015), the experiments were conducted without enough replicates for statistical analysis and thus the statistical significance of the effects of VR on total CNP loss is unknown. Therefore, more data on the effects of VR and SB on the reduction of soil erosion and CNP loss from sloping fields need to be accumulated to understand if these BMPs are effective or not, before VR and SB are recommended to farmers. It is also necessary to investigate the changes in crop growth and yield by implementing VR and SB as both VR and SB may change soil environment for crop growth by reducing the loss of soil and nutrients. In addition, most relevant studies have investigated CNP runoff from upland fields in the dissolved forms, but not in particulate forms associated with soil particles as they focused more on the impact of CNP loss on water quality rather than soil quality (Gascho et al. 1998; Shin et al. 2013; Gu et al. 2018). However, in the view of soil fertility, not only dissolved but also particulate forms of CNP should be taken into consideration (Nie, Zhao, and Qiao 2013; Shi and Schulin 2018).

This study was conducted to investigate the effects of VR and SB on the loss of soil and CNP via runoff from slopping cultivated fields and to assess changes in crop growth and yield by VR and SB. It was hypothesized that 1) both VR and SB may reduce runoff and thus loss of soil and CNP by acting as barriers for the runoff by interrupting water flow toward downslope and 2) the reduced soil and nutrient loss may favor crop growth and yield.

2. Materials and methods

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Topsoil (0–20 cm) and subsoil (20–40 cm) samples were collected from three randomly selected points within the field (10 m × 16 m) using a soil auger. The soil samples were air-dried, passed through a 2-mm sieve, and analyzed for soil texture and chemical properties (Table 1). Soil texture was determined with the standard pipette method (Gee and Bauder 1986). The soil pH was measured at a 1:5 (w:v) soil-to-distilled water ratio using a pH meter (Orion 3 star, Thermo Fisher Scientific Inc., Beverly, MA, USA). Total C and total N were analyzed using a combustion method (Nelson and Sommers 1996) with an elemental analyzer (Flash EA 1112, Thermo fisher Scientific Inc., USA). Inorganic N (NH_4^+ and NO_3^-) was analyzed using the Kjeldahl digestion-distillation method after KCl extraction at 1:5 (w:v) soil-to-2 M KCl ratio (Keeney and Nelson 1982). Total P and available P was analyzed using the ascorbic acid colorimetric method after digestion with perchloric acid and NH_4F extraction of soils, respectively (Kuo 1996). Cation exchange capacity was analyzed using the ammonium acetate extraction method (Summer and Miler 1996). Soil texture was silt loam and soil was alkaline, and other properties are shown in Table 1.

Table 1. Selected properties of the upland field soil.

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2.2. Experimental setting

In the middle of June 2018, nine plots (plot size: 1 m × 8 m) were established for three treatments (no treatment, control; vegetated ridge, VR; sandbag, SB) with triplicates in a completely randomized block design. All aspects of the field, including slope degree and direction, replication, crop planting and cultivation method, and irrigation were consistent across all treatment plots except for the BMP treatments themselves (i.e., control, ...

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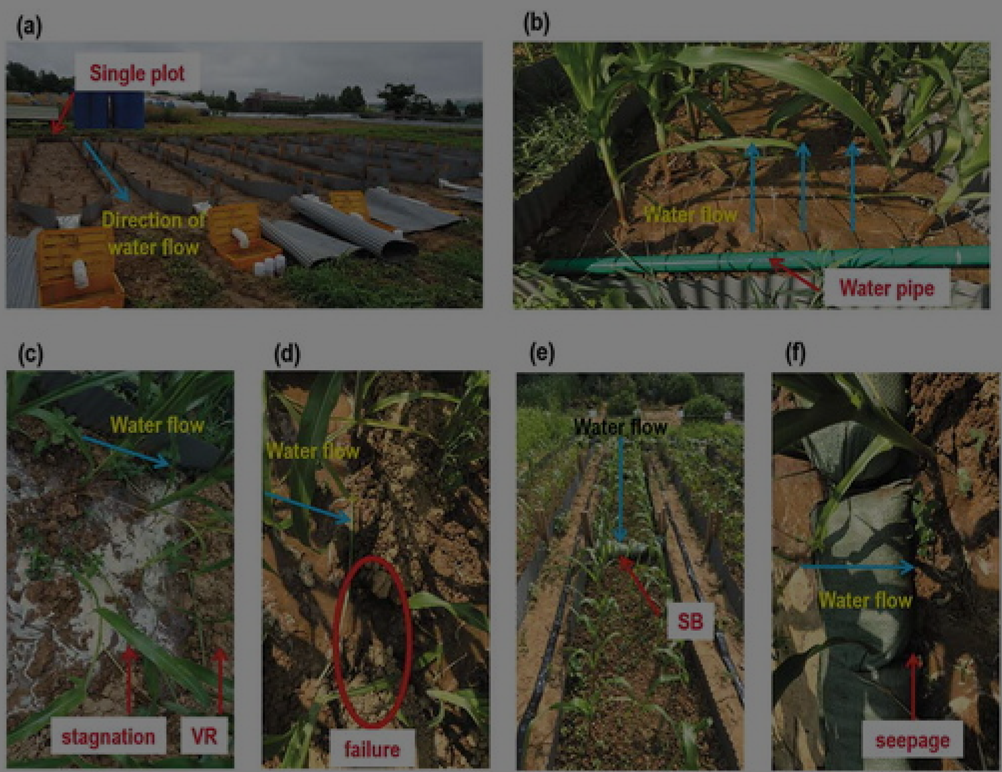
plow pan layer of the soil (20 cm deep) around the plot to collect only the runoff from each of the confined plots (Figure 1a and Fig. S1). At the downslope end of each plot, a flume and a collecting bin (55 cm width × 40 cm length × 30 cm height, 66 L) were installed to collect the runoff water. Three holes (at 10, 15, and 20 cm above the bottom) were drilled on the front side of the bin to install three steel pipes with water meters. This was designed to determine the amount of runoff water by measuring runoff water that was collected in the bin and passed through the steel pipes to the outlet of the water meters. The collecting bins were covered with lids and plastic covers to prevent rainfall entering directly into the bin.

Figure 1. Photos of the experiment: (a) a panoramic view of the plots, (b) supplying water for the artificial runoff experiment, (c) vegetated ridge (VR) and stagnation of water flow by VR, (d) failure of VR by excessive water, (e) sandbag (SB) placed in the plots, and (f) water seepage through gaps between SBs.



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within each VR plot were constructed 15 cm in height, 30 cm in width and, 3 m apart, considering the small size of the plots (Figure 1). During cultivation, volunteers and weeds growing on the ridges were not removed to allow natural vegetation cover on the ridges, as long as they did not interfere with the growth of maize plants adjacent to the ridges. Four sandbags (28 cm × 48 cm) containing approximately 10 kg of soils and gravels from the outside of the plots were installed in a row across the SB plots at the same position as the VRs in the VR plots (Figure 1). The SBs were placed on the soil surface and the SBs were foot-tamped several times to minimize the gaps between the SBs and between SB and soil surface. As SBs were installed a few days after plowing, the soils were soft enough to allow the gaps to be filled with soils naturally by foot tamping. During the field experiment, the VR and SB were fixed if necessary particularly after heavy rainfall.

In one of the three plots for each treatment, a soil moisture sensor (5TM, Decagon Devices Inc., Pullman, USA) was installed at 5–15 cm of depth. Soil moisture was monitored at 5 min interval and stored in a data logger (CR1000, Campbell Scientific, Logan, USA) as an average value over 30 min. An automatic rainfall gauge (TBRG, Caella Rainfall System, UK) was installed at 1 m above the surface beside the field, and rainfall data were stored every 30 min.

2.3. Maize cultivation

Twenty-days old seedlings of maize (Zea mays L. var. ceratina) were transplanted into the plots by hand in two rows (distance 60 cm) along the slope of the plots with a spacing of 30 cm between seedlings on July 4 (Figure 2). Fertilizer was applied one day before the transplanting at 17.4 g N m^{-2} as urea, 3.0 g P_2O_5 m^{-2} as fused phosphate, and 6.9 g K_2O m^{-2} as KCl. Urea was applied once more at 17.4 g N m^{-2} one month after transplanting. During maize growth, weeds were removed by hand to prevent interfere … ated using irrigation … soil moisture content …

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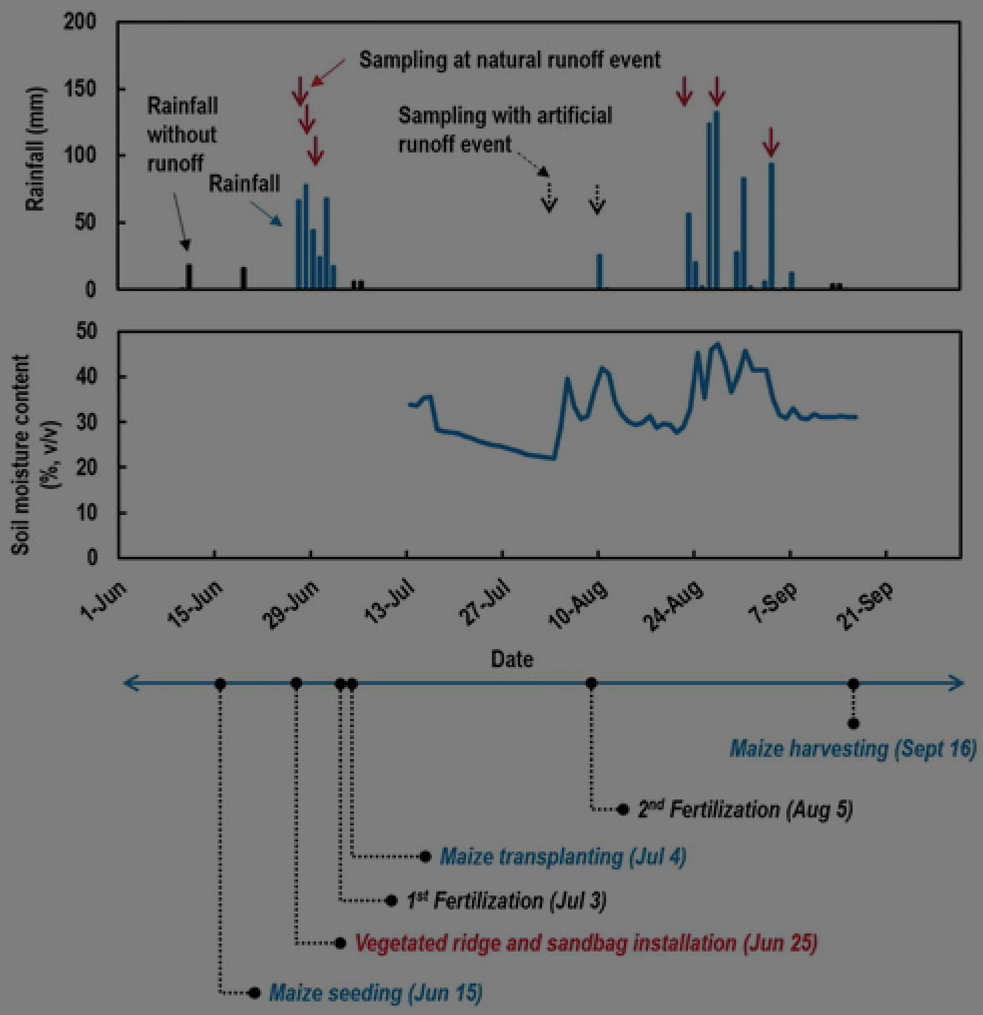

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At harvest (September 16), six individual plants were selected randomly from the upslope, middle, and downslope of each plot and cut from 5 cm above the ground surface. The sampled plants were separated into ears, husks, stalks, and leaves in the field to carefully measure plant biomass and transported to the lab. The plant samples were washed with running water and oven-dried at 60°C to constant weight. Kernels were removed from the dried ears and weighed separately for grain yield

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other six events (on June 27, June 28, June 29 to 30, August 23 to 24, August 25 to 27, and August 30 to September 4) that produced enough runoff were investigated (Table 2). For each rainfall event, when rainfall was not heavy (< 100 mm, events 1–4, Table 2), runoff water was collected directly from the flume in a 1-L sterile plastic container during the event. However, when rainfall was heavy accompanying typhoon (> 200 mm, events 5 and 6), runoff water sample was collected from each bin after the event ceased rather than directly collecting the sample from the flume in the middle of the event to ensure workers' safety. In these cases, soil particles that were eroded from the plots during the event were deposited at the bottom of the bin. After the event ceased, water level in the bin was recorded using a meter stick to calculate the water volume contained in the bin before sampling. Runoff water samples in each bin was homogenized by mixing with a water scoop and sampled in a 1-L container to represent the homogenous water sample during the event. After each sampling, the collecting bin was emptied and cleaned in preparation for the next event. The collected samples were stored in a fridge at 2°C until analysis.

Table 2. Period, cumulative rainfall, and runoff ratio of natural runoff events at different soil moisture status.

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In the natural runoff experiment, runoff ratio (the ratio of runoff water to water received in the plot) could not be determined directly. Initially, we attempted to measure the amount of runoff water using the three water meters installed on the front side of the bin. However, during the first natural runoff event in June, it was found that the water meters did not work properly due to blockage of the pipes with soils and plant debris.

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the length of the plastic pipes to supply water evenly across the plot and cover the entire plot area. The runoff ratio was determined by measuring the amount of water supplied and runoff water. The amount of water supplied was measured using a water meter attached in the irrigation water line, and the amount of runoff water was determined by pumping out the water being collected in the bin using a mechanical pump with a water meter attached at the outlet until the water supply was turned off and runoff ceased. Water pump was not applied to the natural runoff experiment due to electrical safety problem during raining. Runoff water samples were collected directly from the outlet of the flume. In the first artificial experiment, runoff water sample was collected once in the middle of the period of the water supply. In the second experiment, however, water samples were collected twice, in the early (when runoff flow started exiting the flume) and late (after the water supply was turned off) period of the runoff, to observe changes in runoff water quality as the event progressed. Though the rainfall intensity (88–98 mm hr^{-1}) of the artificial runoff experiment conducted in August was much greater than natural rainfall, it is also worthy of investigation runoff ratio and loss of SS and CNP during short but high-intensity rainfall events considering extreme rainfall events caused by climate change. In South Korea, extreme rainfall events of > 980 mm day^{-1} and rainfall intensity over 106.5 mm hr^{-1} have been observed (KMA 2018b).

Another artificial runoff experiment was also conducted after harvest to develop a regression equation between rainfall and runoff ratio for estimation of runoff ratio in the natural runoff events since measurement of runoff water amount from the natural runoff experiment failed due to malfunction of the water meters in the collecting bin. The experiment was conducted twice at a control plot under different soil moisture conditions as runoff ratio was found to be different with soil moisture level during the artificial runoff experiments; i.e., runoff ratio was lower for dry soils than that for wet soils (see Results and Discussion sections). Two weeks after harvest, the control plot
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experiments to estimate the runoff ratio. The irrigation intensity varied from 3.6 to 17.2 mm hr^{-1} (mean: 13.5 mm hr^{-1}) for the first (on dry soils) and 10.1 to 18.5 mm hr^{-1} (mean: 15.9 mm hr^{-1}) for the second (on wet soils) irrigation due to unstable capacity of the water supplier though the target irrigation intensity was set at 17 mm hr^{-1}, which is about twice of the rainfall intensity (8.5 mm hr^{-1}) of the natural rainfall (Table 2).

2.6. Runoff water analyses

The concentrations of suspended solids (SS), dissolved nitrogen (DN), dissolved phosphorus (DP), and dissolved organic carbon (DOC) of runoff water samples were analyzed following the standard methods for water analysis of Korea government (MOE 2017). At first, 1 mL of 35% (w/v) $CaCl_2$ solution was added to a centrifuge bottle containing 450 mL of water sample and shaken with hand for 1 min to facilitate sedimentation by aiding soil aggregation. The water samples were centrifuged at 3500 rpm for 10 min to separate the SS and solution. The clear supernatant was carefully transferred to a plastic bottle for DN, DP and DOC analyses, and the remaining solids were oven-dried at 105°C to a constant weight. The amount of water and solid added by the $CaCl_2$ solution was corrected when SS and CNP concentration were calculated. Dried solids were weighed to determine the concentration of SS in each water sample. For the events 5 and 6 for which sampling was conducted after the rainfall ceased, the remaining runoff water in the bin was concentrated with SS that had settled during the entire duration of each event. Therefore, the SS concentration was re-calculated for the total runoff water by multiplying the ratio of the volume of water in the bin to the volume of total runoff.

The DN was analyzed using the Kjeldahl digestion-distillation method, DP was analyzed with ascorbic acid reduction method after digestion with $K_2S_2O_8$, and DOC was measure … further analyze … C), total N (TN), an … e dissolved and par …

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where C_i is the concentration of SS (g L^{-1}) and CNP (mg L^{-1}) at i^{th} event, V_i is the volume (L) of runoff at i^{th} event, and V_S is the sum of runoff volume for all the events.

Soil and CNP loss (Loss) from the fields (kg m^{-2} for SS and g m^{-2} for CNP) were calculated as follows:

(2)

where C is the concentration of SS (g L^{-1}) and CNP (mg L^{-1}), V is the volume (L) of runoff, A is the area of plot (8 m^2), and 1/1000 is a factor to convert the unit of SS and CNP loads to kg m^{-2} for SS and to g m^{-2} for CNP.

The volume of runoff was calculated using rainfall (mm, RF) and runoff ratio (R_{runoff}) as follows:

(3)

For statistical analysis, data were tested for homogeneity of variance and normality of distribution using Levene's test and Shapiro-Wilk's test, respectively. Data were homogenous and normally distributed. The effects of VR and SB on runoff parameters such as concentration and loss of soil and CNP as well as maize biomass and yield were statistically evaluated with analysis of variance (ANOVA) using the IBM SPSS Statistics 23 (IBM Corp., Armonk, New York, USA). When the treatment effects were significant, the means were separated by the Duncan's multiple range test. The level of significance of all statistical tests was set at $\alpha = 0.05$.

3. Results

3.1. Runoff ratio

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irrigation was > 49.8 mm (Figure 3a). On wet soils, runoff occurred immediately after an irrigation (at 17.6 mm) and runoff ratio increased from 0.73 to 0.93 with increasing cumulative irrigation (Figure 3b). However, the magnitude of the response of runoff ratio to cumulative irrigation changed when the amount of irrigation reached a certain level. Runoff ratio more sharply increased with irrigation from 0.73 to 0.91 when cumulative irrigation was < 88.0 mm, whereas runoff ratio with cumulative irrigation over 106.5 mm increased less responsively to water supply from 0.92 to 0.93.

Table 3. Details of artificial runoff experiments to test the effects of vegetated ridge (VR) and sandbag (SB) on runoff and loss of soils and nutrients from upland field.

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Figure 3. Regression equations between cumulative irrigation amount (x variable) and runoff ratio (y variable): (a) for dry soil and (b) for wet soil. The soil moisture contents were 21.7% and 37.2% (v/v) for dry and wet soils, respectively. In (a), runoff did not occur for low cumulative irrigation, and thus one data point was not included in the regression (n = 11). In (b), as the pattern of the relationship between cumulative irrigation and runoff ratio changes when cumulative irrigation increased above 100 mm, two different equations were developed (five data points with irrigation below 100 mm, and seven data points with irrigation above 100 mm). The equations were expressed up to six decimals for accuracy.

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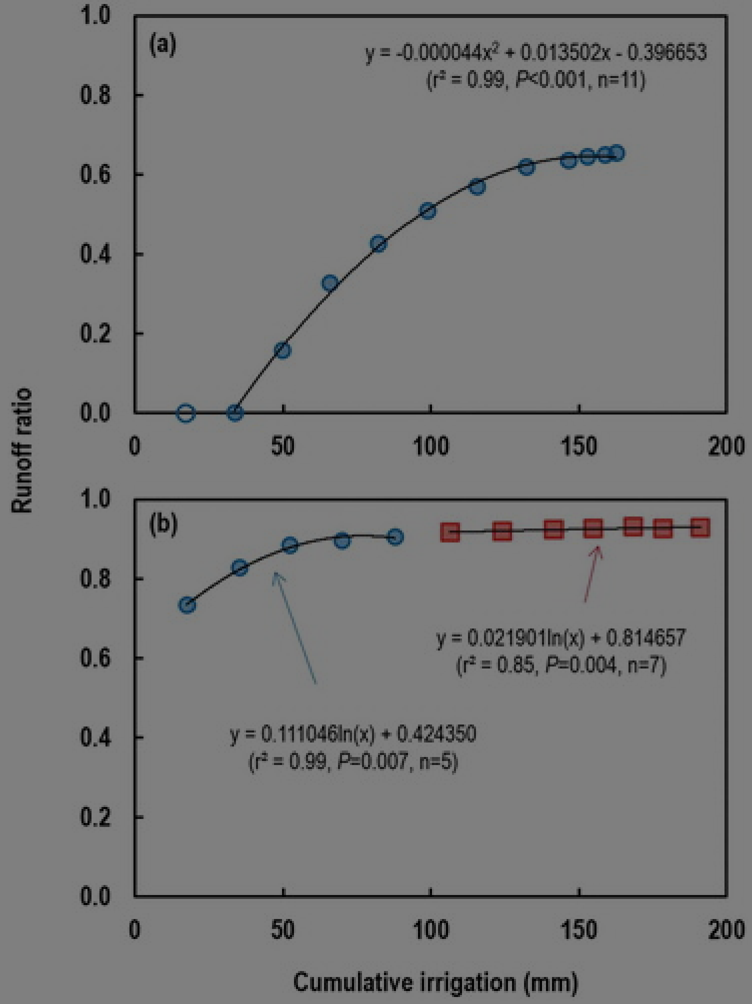

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As runoff ratio did not differ between treatments in the artificial runoff experiment (Table 3), it was possible to apply the same regression equation between cumulative irrigation (i.e., rainfall) and runoff ratio (Figure 3) to all the treatment plots, but separately for dry and wet soils, to calculate runoff ratio for the natural runoff events during the maize growth period. The runoff ratio of natural runoff events ranged from 0.31 to 0.91 with a considerably higher runoff ratio under wet than dry soil moisture status (Table 2).

3.2. Soil and CNP loss, and maize growth

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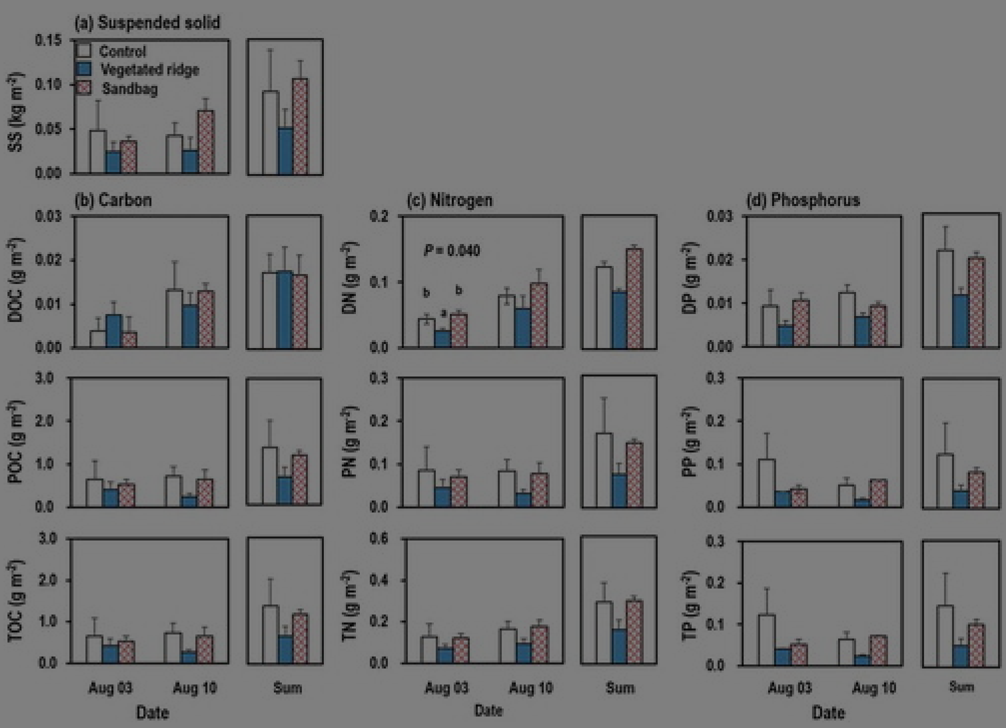
artificial runoff experiment, it was found that the concentrations of SS and CNP was not different between the early and late runoff for control and SB treatment (Figure 5). For VR treatment, however, the concentrations of SS and CNP were lower for the late runoff than for the early runoff.

Figure 4. Loss of soil and nutrients from the control, vegetated ridge, and sandbag treatment plots by irrigation (artificial runoff experiment) conducted during dry seasons (Aug 3 and 10): (a) suspended solids (SS), (b) carbon (C), (c) nitrogen (N), and (d) phosphorus (P). The details of the experiment are provided in Table 3. For C, N, and P, both dissolved (DOC, DN, DP, respectively) and particulate (POC, PN, and PP, respectively) forms were analyzed, and the total organic C (TOC), total N (TN), and total P (TP) were calculated by summing dissolved and particulate forms. Vertical bars are standard errors of the means (n = 3). When the values were different at α = 0.05, P values were provided. The different lower-case letters above the values indicate that they are significantly different.



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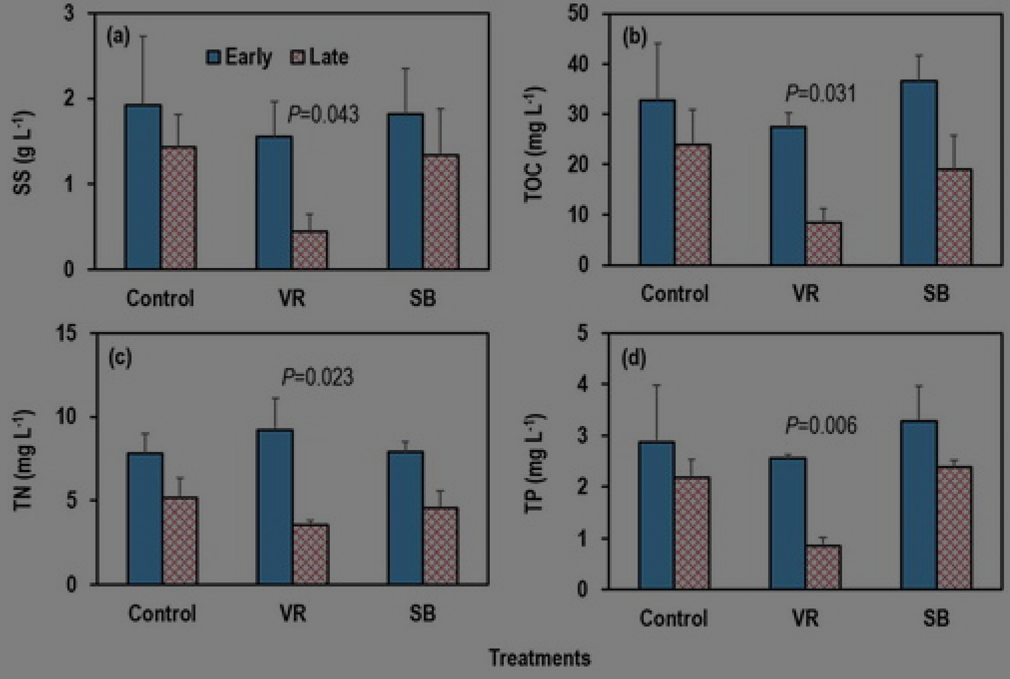

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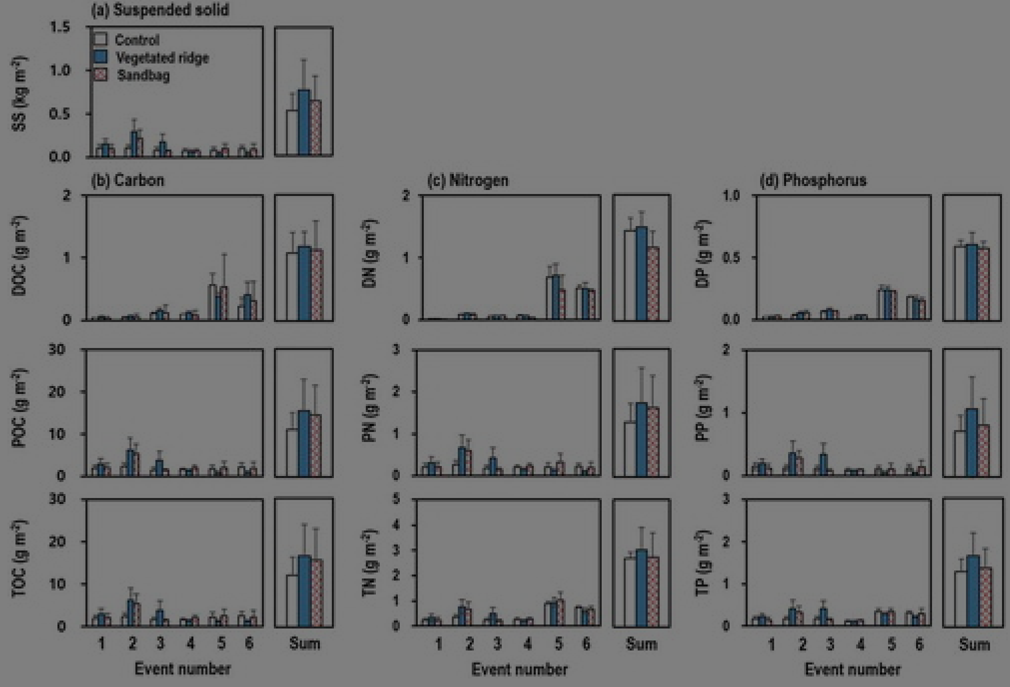
In the natural runoff experiment, similar to the artificial runoff experiment, neither the concentrations nor loss of SS and CNP in the runoff water were different among the treatment plots (Table S2–5 and Figure 6). The EMCs across all the treatments were 9.3 g L^{-1} for SS, and 35.6, 6.2, and 3.1 mg L^{-1} for TOC, TN, and TP, respectively (Table S2–5). On average across the treatments, the total loss of soil and CNP by rainfall during the maize growth period were 0.65 kg m^{-2} for SS, 14.79 g m^{-2} for TOC, 2.84 g m^{-2} for TN, and 1.45 g m^{-2} for TP. Similar to the artificial runoff experiment, the particulate forms of CNP accounted for more than 50% of the total loss (92.4%, 54.4%, and 59.4% of TOC, TN, and TP, respectively).

Figure 6. Loss of soil and nutrients from the plots of control, vegetated ridge, and sandbag treatments by rain (natural runoff experiment): (a) suspended solids (SS), (b) carbon (C), (c) nitrogen (N), and (d) phosphorus (P). The details of the experiment for each event are provided in Table 2. For C, N, and P, both dissolved (DOC, DN, and DP, respecti... alyzed, and the total ... umming dissolve... ans (n = 3). As treat... es were not prov...



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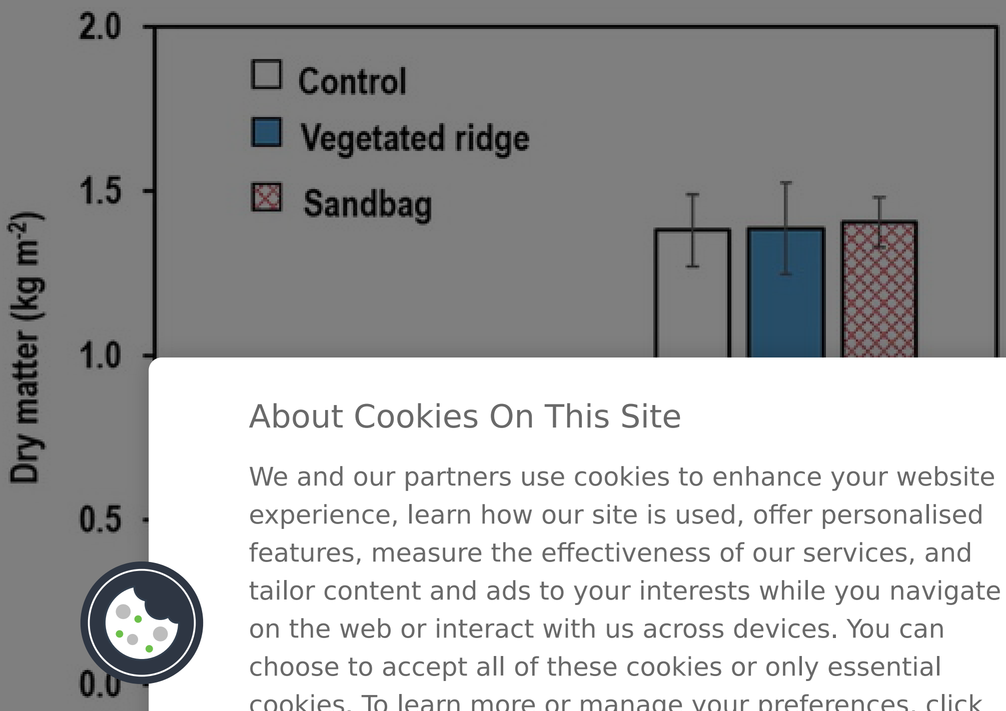
Grain yield and total biomass of maize were not affected by VR and SB treatments, ranging from 0.61 to 0.68 kg m^{-2} for grain yield and from 1.38 to 1.41 kg m^{-2} for total biomass (Figure 7).

Figure 7. Grain yield and total biomass of maize grown with no treatment (control) and vegetated ridge and sandbag treatments. Vertical bars are standard errors of the means (n = 3). As treatment effects were not significant for all variables at α = 0.05, P values were not provided.



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4. Discussion

4.1. VR and SB did not decrease runoff ratio

No effect of VR and SB on the runoff ratio rejects our first hypothesis. During the artificial and natural runoff experiments, we observed ridge played as a barrier for water flow (Figure 1c) but ridge failed in the early period of the artificial runoff event with high irrigation intensity (Figure 1d). Ridge failure occurs through breaching of ridge by water when water stored in furrow exceeds the water storage capacity of the ridge (Xu et al. 2018). In many experiments with contour ridge system, failure of contour ridge to store water loss has been reported (Liu et al. 2015; Xu et al. 2018). The threshold rainfall intensity to cause ridge failure differ with studies, e.g., 40 mm hr^{-1} for Liu et al. (2015) and 75–100 mm hr^{-1} for Xu et al. (2018), depending on the experimental conditions such as slope and soil properties. In our study, the irrigation intensities applied in the first and second artificial runoff experiments were 87.9 mm hr^{-1} and 89.1 mm hr^{-1}, respectively, falling in the range reported by Xu et al. (2018) in which artificial rainfall experiment was conducted with a similar plot size (1.5 m × 8 m) but steeper slope (5°, approximately 8.8%) compared to our study. In the Xu et al. (2018), ridge failure occurred between 20 and 30 min after the rainfall event, resulting in no difference in total runoff between control and ridge treatment. In the second artificial runoff experiment of our study, the higher SS and CNP concentrations of the water samples collected in the early period of the event than in the late period indicate that most erodible soils and CNP are likely to be lost by ridge failure during the early period of the event. Similarly, for SB treatments, seepage of water through gaps between SBs and between SB and soil surface was found (Figure 1e and f) despite the efforts made to minimize the gaps by foot-tamping, suggesting that SB is not an effective as measure to store runoff water unless the soils around SBs are concrete enough t… …ss is available…

Thou… …ter runoff ratio… …s conducted during m… …al soil moisture… …ent (Darvish… …d with runoff of rainfall compared to dry soils (Shahrban et al. 2018). Similarly, in the artificial runoff experiment conducted after maize harvest, the decreased increment of runoff ratio with increasing cumulative irrigation amount (Figure 3) further suggests that the infiltration rate of the soils became lower with increasing soil moisture content by water supply (Darvishan et al. 2015).

4.2. VR and SB did not reduce soil and CNP loss

Our results on the effects of VR and SB on soil and CNP loss show that VR and SB are not as effective as expected, and thus reject our hypothesis though it was believed that VR and SB can reduce soil erosion and nutrient loss from upland fields (Kim et al. 2012; Guyer 2018). For example, Kim and Kim (2015) reported that VR constructed on upland (5 × 22 m^2, slope: 6–8%) reduced loss of SS (40.4–73.7%), DOC (49.1–53.7%), DN (26.7–67.2%), and DP (52.7–91.8%). Kim et al. (2012) also found reduction in the loss of SS (65.3%), DOC (43.3%), DN (81.8%), and DP (54.3%) by VR from upland fields (5 × 22 m^2, slope: 3%). However, in these studies, the experiment was conducted with single or two plots, and thus the statistical significance of the reduction of SS and CNP by VR has not been tested. In our study with triplicated plots, arithmetic means of loss of SS, TOC, TN, and TP of VR treatment were lower than the control in the artificial runoff experiments; however, the effects were not statistically significant (Figure 4).

No difference in soil and CNP loss between treatments is consistent with the results that neither runoff ratio (Table 3) nor the concentrations of soil and CNP in runoff water was affected by VR and SB (Table S1–5). However, as the performance of ridges is affected by ridge height and width as well as field slope (Liu et al. 2015), more comprehensive studies are required to establish a guideline to construct more stable VR. In this context, covering VR with perforated plastic film that may allow vegetation growth while physically supporting VR and covering SBs with plastic film or placing another SB between ... o correct the flaws of ...

The aver... $^{-2}$) found in our s... a (3.77 kg m^{-2} ... of the experim... of upland with slop... 4%, the greater CNP loss in particulate forms associated with soil loss than that in dissolved forms highlights the importance of erosion-induced loss of CNP (Shi and Schulin 2018). The contribution of CNP loss in particulate form to total loss found in the present study (92.4%, 54.4%, and 59.4% of TOC, TN, and TP, respectively) are similar for other studies; e.g., 93% for TOC (Hua, Zhu, and Wang 2015), 54% for TN (Chen et al. 2012), and 71% for TP (Sharma, Bell, and Wong 2017). Such loss of particulate CNP via soil erosion not only hampers soil C sequestration as C associated with soil particles is stable against microbial decomposition (Lim et al. 2017; Ran et al. 2018) but also deteriorates soil quality since particulate N and P are nutrient reservoir for plant uptake in the soils (den Biggelaar et al. 2004). In addition, particulate N and P may have a long-term adverse impact on surface water quality through dissolution and microbial mineralization (Sharpley, Smith, and Naney 1987). Therefore, the substantial contribution of particulate forms to total CNP loss strongly suggests that not only dissolved but also particulate CNP associated with SS should be considered in the study for the estimation of the soil and CNP loss through rainfall-induced surface runoff to address both soil degradation as well as water pollution.

4.3. VR and SB did not increase maize yield

Grain yield of maize (0.61 to 0.68 kg m^{-2}) of our study (Figure 7) is within the range (0.2 and 1.0 kg m^{-2}) of global yield data (Rusinamhodzi et al. 2011) that differ with soil type and agricultural management such as fertilization and tillage management (Wang et al. 2015; Hashim et al. 2017). No difference in maize yield across treatments coincides with the insignificant effect of VR and SB on the loss of SS and CNP. It was expected that if VR and SB were able to reduce soil erosion and CNP loss, it might lead to an increase in maize yield through improved soil conditions compared to the control. It has been reported that other BMPs can increase maize yield by reducing the loss of nutrients; e.g., in a meta-analysis study, Qin, Hu, and Oenema (2015) reported that straw m

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accelerated convergent flow. For SB, SS and CNP might have been lost by seepage water through gaps between SBs and between SB and soil surface. Considering the feasibility of VR and SB installation as well as cost-effectiveness for farmers, however, further studies for the correction of the flaws of VR and SB are required to improve their design and applicability to larger-scale farms. Since there was a substantial loss of nutrients associated with soil particles, physical reinforcement of the structures of VR and SB may lead to a reduction in soil erosion and subsequently, nutrient loss. We are aware of the limitations of this study as runoff ratio of natural rainfall events were not directly quantified but rather estimated using the relationship between cumulative rainfall and runoff ratio, and sampling was conducted only once during the event, missing possible changes in the soil and CNP loss in runoff with time. Nevertheless, as this study was conducted under the same experimental procedures across the plots where the field conditions were consistent except for the treatments imposed, we believe that the results provide a novel evidence of the field performance of VR and SB and suggest the necessity of strategies to improve their performance.

Supplemental material

Supplemental_materials_revised.docx

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Disclosure statement

No poter

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Additional information

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