Agriculture, Ecosystems and Environment 311 (2021) 107266

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

Impact of soil thickness on productivity and nitrate leaching from sloping cropland in the upper Yangtze River Basin

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ARTICLE INFO

Keywords:
Winter wheat
Summer maize
Lysimeters
Yield-scaled nitrate leaching
Agriculture non-point source pollution

ABSTRACT

Shallow soils are widely distributed in mountainous and hilly areas due to severe soil erosion. However, the impacts of soil thickness on soil productivity, water and nutrient retention in shallow cropland soils have not been well documented. This study was conducted to investigate how soil thickness affects soil productivity and nitrate leaching from sloping croplands in the upper Yangtze River Basin, China. Free-drained lysimeters on sloping cropland with soil thicknesses of 20 (ST1), 40 (ST2), 60 (ST3), 80 (ST4) and 100 (ST5) cm were used to monitor soil moisture, surface runoff and nitrate leaching. The results showed that total crop yields during an entire winter wheat-summer maize rotation year (October 2017-September 2018) for ST1 to ST5 were 2.38 ± 0.07, 3.22 ± 0.01, 6.43 ± 0.61, 8.21 ± 0.56 and 8.58 ± 0.29 Mg ha^{-1}, respectively. The annual cumulative total nitrogen (N) loss loadings via surface runoff and leaching for ST1 to ST5 were 21.09 ± 1.54, 13.08 ± 0.79, 5.61 ± 0.36, 3.49 ± 0.27 and 1.96 ± 0.22 kg N ha^{-1}, respectively. The annual cumulative nitrate leaching loadings for ST1 to ST5 were 18.41 ± 1.07, 11.27 ± 0.56, 4.93 ± 0.45, 3.05 ± 0.32 and 1.66 ± 0.12 kg N ha^{-1}, respectively, which accounted for more than 84 % of the cumulative total N loss through hydrological processes. This finding indicates that leaching dominates the hydrological N loss in sloping cropland. Moreover, significant differences were observed in yield-scaled nitrate leaching losses among ST1 (7.74 ± 0.62), ST2 (3.49 ± 0.18) and ST3 (0.78 ± 0.13 kg N Mg^{-1}) ($P < 0.05$), while no significant differences were found among ST3 (0.78±0.13), ST4 (0.37±0.02) and ST5 (0.19±0.01 kg N Mg^{-1}). This finding implies that if the soil thickness is greater than 60 cm, then it may be possible to maintain crop yields and mitigate nitrate leaching losses on sloping croplands. Therefore, a soil thickness of 60 cm is recommended as a threshold soil layer for basic water and nutrient retention as well as land reclamation and restoration of degraded cropland suffering from severe soil erosion. Soil thickness is a critical index for evaluating soil functions for water and nutrient retention, crop productivity improvement and agricultural non-point source pollution control.

1. Introduction

Intensive agriculture requires substantial amounts of synthetic fertilizer applications and results in non-point source pollution loadings; China ranks the highest in the world in terms of intensive agriculture, and the associated negative environmental impacts have attracted great attention (Zhang et al., 2015). Agriculture faces substantial challenges in terms of ensuring global food security by increasing yields while reducing environmental costs (Foley et al., 2011; Tilman et al., 2011). Nitrogen (N) is an essential nutrient in agricultural ecosystems, but it is also a major pollutant in the environment (Zhang et al., 2015; Zhou et al., 2016; Notaris et al., 2018; Jungers et al., 2019). When synthetic fertilizer N exceeds the level of crop demand, surplus nitrate is accumulated in soil, which may cause excessive N leaching to groundwater (Klaus and Henning, 2006; Zhu et al., 2009a; Li et al., 2016; Lu et al., 2019). Eighty percent of the monitoring wells in 18 administrative regions in China have reported groundwater nitrate concentrations exceeding 30 mg L^{-1} (The Minister of Water Resources of the People's Republic of China, 2016). Intensive croplands are the main source of the nitrate that released into the hydrosphere (Sebilo et al., 2013; Asada et al., 2018). Agricultural non-point source (AGNPS) pollution is a ubiquitous environmental challenge worldwide (Serio et al., 2018;

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https://doi.org/10.1016/j.agee.2020.107266
Received 8 September 2019; Received in revised form 28 September 2020; Accepted 22 November 2020
Available online 10 February 2021

Sidemo-Holm et al., 2018; Wang et al., 2019a) and has become one of the main causes of degraded water quality in China (Yang et al., 2018). N loss through leaching and runoff from agricultural fields is an important source of AGNPS pollution that can result in groundwater contamination and surface water eutrophication (Huang et al., 2017).

According to an increasing number of field observations, N leaching varies with environmental conditions, including hydrological and climatic factors, and soil properties, such as the nitrate content, soil organic matter, soil moisture, soil texture and soil thickness (de Ruijter et al., 2007; Velthof et al., 2009; Zavattaro et al., 2012; Chen et al., 2014). Water leakage is considered to be the main driving factor of N leaching (Zhu et al., 2009a; Padilla et al., 2018; Sun et al., 2018).

Soil thickness is a basic soil property and a fundamental variable in soil quality especially in assessment of soil degradation in the mountainous area (Dietrich and Perron, 2006; Patton et al., 2018). In an assessment of soil degradation, the soil-layer thickness is divided into 5 levels, level I ≥ 100 cm; level II 60−100 cm; level III 30−60 cm; level IV < 30 cm;, and level V bare rock (Zhang and Gao, 1997). Shallow soil (mainly < 60 cm) is a special form of soil degradation (Zhu et al., 2009b), especially in regions with hillslope or mountainous agriculture that have experienced serious soil erosion. Sloping cropland is susceptible to soil erosion, leading to sediment yield, topsoil loss, and land degradation issues such as soil "shallowness" (Zhu et al., 2008). Surface runoff and leaching along with soil erosion are responsible for nutrient loss and cropland productivity declines (Mamedov and Levy, 2019), which may have a risk of causing AGNPS pollution if the surface runoff entered into lakes or water, or the leaching water reached the depth of groundwater (Al-Wadaey and Ziadat, 2014; Posthumus et al., 2015; Issaka and Ashraf, 2017). NO_3^--N is one of the most typical and widespread water pollutants (Zhu et al., 2009a), while leaching from agricultural soils has promoted much concern about water pollution and human health due to its contribution to NO_3^--N losses (Chen et al., 2010; Zhang et al., 2017). A previous study showed that nitrate leaching losses were inversely proportional to soil depth (Hu et al., 2011). It has been reported that soil water storage can positively affect soil N retention (Yan et al., 2019), and soil thickness can determine runoff responses, that is, thicker soil can reserve more water in the soil profile (Patton et al., 2018). Thus, the soil-layer thickness is of great importance for N leaching (Doole, 2015). Previous studies on soil thickness mainly focused on the basic phenomena of crop yield and soil erosion (Zhu et al., 2009b; Fu et al., 2011). However, the role of soil thickness in affecting nitrate leaching is rarely estimated. To date, there is a lack of systematic and quantitative research on impacts of soil thickness on productivity and non-point source pollution. Because of great pressure of non-point source pollution, much effort should be conducted to reduction of nitrogen loss from sloping croplands as well as soil erosion control. Therefore, the impacts of the soil thickness of sloping cropland on water, nitrogen loss and land productivity should be considered.

The upper Yangtze River Basin (hereafter the upper YRB) with an area of 1.006×10^6 km^2 is an important food-producing base for hilly and mountainous regions in China (Xu et al., 2019). Cropland in the upper YRB covers an area of 1.5×10^7 ha, of which 60 % is sloping cropland susceptible for soil erosion due to intensive cropping and high rainfall (Zhang et al., 2003; Li et al., 2013). Water and nutrients flow away with runoff water, resulting in decreases in soil fertility (Comino et al., 2016; Chen et al., 2017), land productivity degradation (Tian et al., 2016), and AGNPS pollution (Xu et al., 2015). Land degradation is evident in the upper YRB due to long-term soil erosion, which has caused the obvious characteristic of soil "shallowness" (Zhu et al., 2003, 2009b). Extremely high loadings of leached nitrate leaching aggravate AGNPS pollution (Zhu et al., 2009a), worsening water quality across most of the water bodies in the YRB (Sun et al., 2013; Chen et al., 2017). AGNPS pollution has become a particularly serious problem that requires urgent solutions. Several studies have focused on measures to control N loss via hydrological modifications, such as biochar addition (Ding et al., 2010), crop covers (Gabriel et al., 2012), contour hedgerow

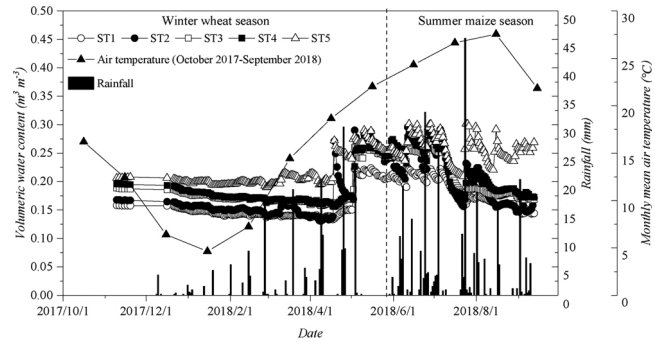

Fig. 1. Dynamic changes in soil moisture in response to rainfall and air temperature.
Note: Treatments ST1, ST2, ST3, ST4 and ST5 represent plots with soil thicknesses of 20, 40, 60, 80 and 100 cm, respectively.

intercropping (Wang et al., 2012) and reductions in fertilizer applications (Hoogendoorn et al., 2017). However, the control effect of current measures is limited for the upper YRB due to the widespread distribution of thin soils and severe N leaching. Improving the productivity of degraded soils is essential to stopping the vicious cycle of land degradation (Pluer et al., 2020). Therefore, land reclamation is urgently needed and soil thickness should be attached with great importance. Therefore, the soil thickness may be a key restricting factor and should be stressed in terms of soil productivity, water and nutrient retention.

A hillslope free-drain lysimeter study was conducted to determine how the soil thickness influences crop productivity and hydrological N losses. Hypothetically, thicker soil thickness may improve crop productivity and reduce nitrate leaching. The purpose of this study was to identify (1) the impacts of soil thickness on productivity, (2) the influence of soil thickness on hydrological N losses via surface runoff and leaching, and (3) the threshold soil thickness for water and N retention with respect to the restoration of degraded sloping cropland.

2. Materials and methods

2.1. Site description

The field experiment was carried out in 2017 and 2018 at the Yanting Agro-Ecological Station of Purple Soil, Chinese Academy of Sciences, a member station of the Chinese Ecosystem Research Network (CERN), at an altitude of 400–600 m above mean sea level in the central Sichuan Basin, upper Yangtze River, China (N 31°16′, E 105°28′). The average temperature is 17.3 ℃. The annual mean precipitation is 836 mm and approximately 70 % of the annual precipitation occurs from May to September. The temperature and rainfall for growing seasons are shown in Fig. 1. The experimental soil used in this investigation is known locally as 'purple soil' due to its color and is classified as Pup-Orthic Entisol in Chinese Soil Taxonomy and Eutric Regosol in the Food and Agriculture Organization (FAO, 1990) Soil Classification or Udorthent in the US Department of Agriculture (USDA) Taxonomy (Gong, 1999). Purple soil is a valuable soil resource for agriculture in China and has a rich mineral composition, a good cultivation capability and a high natural fertility and productivity (Zhu et al., 2008). Moreover, purple soil (mainly cropland), with an area of approximately 219,880 km^2 in China, is distributed widely in the upper YRB (He, 2003). The soil thickness of this typical Regosol ranges from 20−100 cm, with the soil thicknesses of 0−20 cm, 20−40 cm, 40−60 cm and 60−100 cm accounts for 16 %, 32 %, 41 % and 11 % of the total, respectively (Zhu et al., 2009b). In addition, the soil has a typical soil-bedrock binary structure (Xiong and Li, 1986). Due to the topography and the lack of irrigation infrastructure, the purple soil croplands in this region are essentially a rain-fed agricultural system. The specific soil used in this experiment for the plow layer (0−20 cm) is a loam soil. The soil

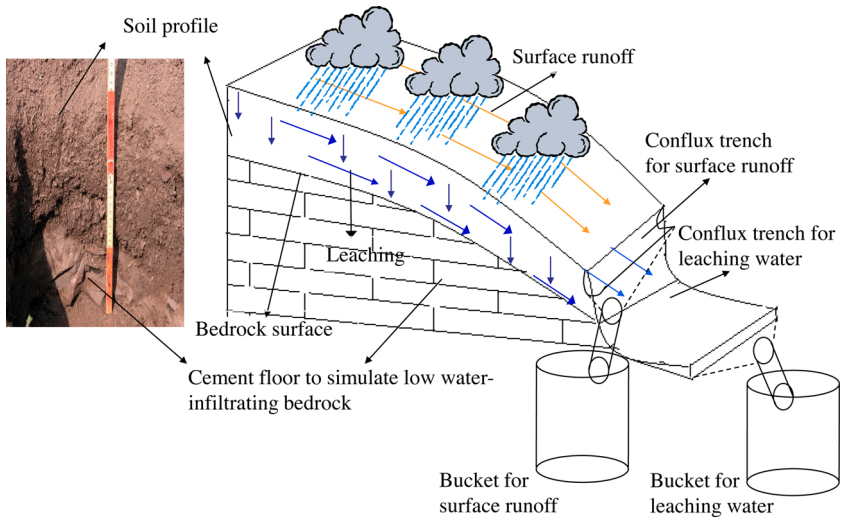

Fig. 2. Schematic illustration of runoff plot design.

properties were similar in the trial, and the average values were as follows, pH of 8.21, soil organic carbon (SOC) of 9.45 g kg^{-1}, total N content of 0.70 g kg^{-1}, alkali-hydrolyzed N content of 42.29 mg kg^{-1} and saturated hydraulic conductivity of 16.8 mm h^{-1}. A regular cropping system of winter wheat (*Triticumaestivum L.*) and summer maize (*Zea mays L.*) rotation has been adopted in upland cropland for more than 50 year. This cropping system is representative of cereal productions systems in China (Li et al., 2014), which playing an important role in cereal production in the upper YRB.

2.2. Experimental design

Field monitoring of hydrological N losses were conducted in plots with free-drained lysimeters. The design of the free-drained lysimeters is similar to that reported by Zhu et al. (2009a, Fig. 2). These free-drained lysimeters measured N losses via different hydrological pathways (surface runoff and leaching). The soil thickness treatments included five soil thicknesses (20, 40, 60, 80 and 100 cm as treatments ST1, ST2, ST3, ST4 and ST5, respectively) with three replicates. The lysimeter plot had an area of 5 m (length) by 1.5 m (width) and a slope gradient of 6.5° which simulates median slope gradients of sloping cropland for cereal production in the upper YRB. The plots were hydrologically isolated with partition walls and a cement base down to 20, 40, 60, 80 and 100 cm to simulate soil thicknesses of 20, 40, 60, 80 and 100 cm, respectively, and to avoid unexpected seepage to the individual plot. Water conflux troughs were built on the topsoil to collect surface runoff and on the bedrock to monitor leaching water. The conflux trough of leaching water was excavated 10 cm below the soil-bedrock interface and filled with clean arenaceous quartz and pebble to the level of the soil-bedrock interface (Fig. 2). The outlet of leaching water was built down to 30, 50, 70, 90, and 110 cm from the soil surface (all down to 10 cm from the bedrock surface, Fig. 2), corresponding to soil thickness treatments of ST1 to ST5, respectively. Buckets for collecting water samples were installed under each corresponding conflux trough from both surface runoff and leaching.

Winter wheat (*Triticum aestivum L.*) was planted in the experimental plots from middle October to May of the next year and then rotated with summer maize (*Zea mays L.*) from May to September. In the winter wheat season, inorganic N fertilizer (NH_4HCO_3), phosphorus and potassium were applied before planting at rates of 130 kg N ha^{-1}, 90 kg P_2O_5 ha^{-1}, and 36 kg K_2O ha^{-1}, respectively. In the summer maize season, the N application rate was changed to 150 kg N ha^{-1}, while the same amounts of P_2O_5 and K_2O were applied. All fertilizers were applied in one dose at the beginning of each crop season by deep fertilization to minimize the loss of nitrogen by ammonia volatilization. The fertilization and crop rotation scheme represent common local practices. Winter wheat was sown on 9 November 2017 and summer maize was sown on 24 May 2018. From October 2017 to September 2018, irrigation was not performed because of sufficient rainfall.

2.3. Hydrological N loss measurements

Soil N losses via surface runoff and leaching were monitored of an intensively managed winter wheat-summer maize rotation system. Free-drained lysimeter plots were used for surface runoff and leaching monitoring. Discharges of surface runoff and leaching water were measured following each runoff event. The water samples were stored at 4 ℃ and analyzed within 48 h. The total N (TN) was digested with an alkaline potassium persulfate solution and then analyzed together with filtering samples through a 0.45 μm membrane. The concentrations of TN, and nitrate N (NO_3^--N) were analyzed using an Auto Analyzer-AA3 (SEAL, Germany).

The water flow discharge, N content, and flux are hereafter reported as the means of the three replicated measurements. The total N and nitrate loss loadings separated into individual plots for each single runoff event were calculated as follows:

$$Q_i = C_i \times q_i/100 \quad (1)$$

where Qi represents the N loss loadings via surface runoff or leaching (kg N ha^{-1}), Ci represents the concentration of the water sample in each rainfall event which caused surface runoff or leaching event (mg L^{-1}), and qi represents the water loss loadings per unit area (mm) in an individual rainfall event which caused surface runoff or leaching event (Zhu et al., 2009a).

The annual cumulative N loss loadings (Q) during the rotation year (annual here means the "rotation year" during the period through October 2017 to September 2018, the same below) was calculated as follows:

$$Q = \sum_{i=1}^{n} Q\mathrm{i} \quad (2)$$

where n is the number of surface flow or leaching events during the monitoring period.

The annual cumulative crop-yield NO_3^--N leaching of the rotation year was calculated as follows:

$$Q_y = Q/(Y_w + Y_m) \quad (3)$$

where Q_y represents the annual cumulative yield-scaled NO_3^--N leaching (kg N Mg^{-1}), Q represents the cumulative NO_3^--N loss loadings (kg N ha^{-1}), Y_w represents the yield of wheat (Mg ha^{-1}); and Y_i represents the yield of maize (Mg ha^{-1}).

2.4. Soil sampling and plant harvesting

After each rainfall event that caused leaching, disturbed soil samples (0−20 cm) were collected for each single runoff event after water sample collection to measure nitrate and ammonium N during the crop growth period. Soil samples taken from the topsoil (0−20 cm) with a soil auger were mixed for each plot (one treatment with three paralleled plots, i.e. one treatment with three paralleled soil samples) to obtain a specific representative soil sample. All soil samples were sealed in plastic bags immediately after sampling and then stored at 4 ℃ until ammonium and nitrate extraction. All soil samples were analyzed for ammonium and nitrate with an Auto Analyzer-AA3 (SEAL, Germany). After harvest (both wheat and maize seasons), undisturbed soil cutting ring samples and regular soil samples were taken from all plots at 20-cm intervals to a depth of 100 cm to measure the soil bulk density and soil NO_3^--N contents to calculate the soil N stock.

The wheat and maize were harvested from all plots, while the crop yields and biomass values were recorded to assess the productivity for different soil thickness treatments. At harvest, wheat and maize plants were separated into roots, stems and leaves, and grains. Roots were recovered from the soil by gently washing them with a low flow from sprinkler. Collected plant samples were dried at 60℃ until the weight of the plants became constant and then weighed to determine the dry matter yield, and the N concentration of the plant samples were analyzed to calculate the N uptake. The TN content of the samples was determined with an Elementar instrument (Hanau, Germany).

2.5. Soil nitrate stock

The soil bulk density was calculated as follows (Bao, 2000):

$$B_s(k) = M_d/V \tag{4}$$

where B_s(k) represents the soil bulk density in the k layer (g cm^{-3}), M_d represents the dry weight of soil (g), and V represents the volume of soil cutting ring sample (100 cm^3).

The soil nitrate stock was calculated as follows:

$$SNNS_s = C_s(k) \times B_s(k) \times D_s(k) \times 0.1 \tag{5}$$

where $SNNS_s$ represents the soil nitrate stock (kg N ha^{-1}), C_s(k) represents the soil nitrate content in the k layer (mg N kg^{-1}), B_s(k) represents the soil bulk density in the k layer (g cm^{-3}), and D_s(k) represents the soil thickness in the k layer (cm).

The soil nitrate stock of all soil layers was calculated as follows:

$$SNNS = \sum_{k}^{n} SNNSs \tag{6}$$

where n represents the number of soil layers.

2.6. Statistical analysis

All statistical analyses were performed with SPSS 22.0 (SPSS Inc., USA) and Origin 2017 (Origin Lab Corporation, USA). The results were subjected to ANOVA, followed by the least significant difference test (*LSD*, $P < 0.05$). In addition, linear regression analysis was used to identify the relationship between NO_3^--N leaching loadings and N uptake by crops as well as crop yields.

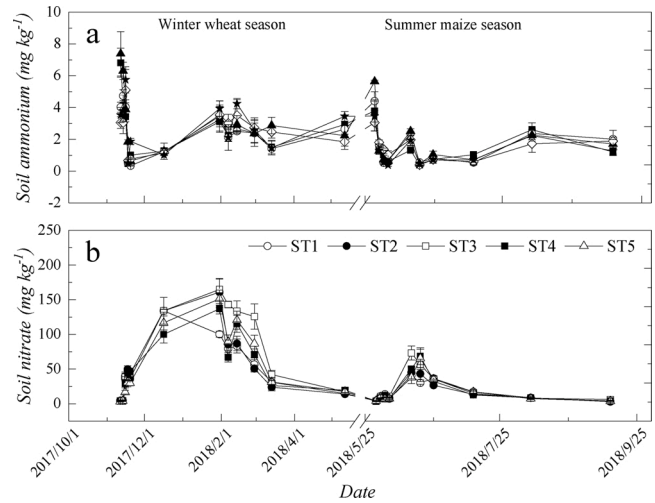

Fig. 3. Changes in topsoil inorganic nitrogen contents during the rotation (October 2017-September 2018).
Note: Fig. 3a shows changes in soil ammonium contents. Fig. 3b shows changes in soil nitrate contents. Treatments ST1, ST2, ST3, ST4 and ST5 represent plots with soil thicknesses of 20, 40, 60, 80 and 100 cm, respectively. Error bars represent the standard error of three replicates.

3. Results

3.1. Dynamic change in soil moisture

The soil (0−20 cm) moisture levels for different soil thicknesses are shown in Fig. 1b. The soil moisture remained relatively stable in the winter wheat season due to minimal rainfall, whereas the soil moisture increased sharply once a heavy rainfall event happened in the summer maize season and remained relatively high due to frequent rain (Fig. 1b). The seasonal change patterns of the soil moisture that responses to rainfall were similar for the five soil thickness treatments. The same sequence (ST1 < ST2 < ST3 < ST4 < ST5) of the soil volumetric water contents were found in both the winter wheat and summer maize seasons, with range of 0.145−0.208 and 0.190−0.260 m^3 m^{-3}, respectively. The daily average soil volumetric water contents were also significantly different among the treatments and obeyed the following sequence, ST1 < ST2 < ST3 < ST4 < ST5 ($P < 0.05$), with values of 0.166, 0.186, 0.194, 0.200 and 0.232 m^3 m^{-3}, respectively.

3.2. Dynamic change in the inorganic N content in the soil

In both the winter wheat and summer maize seasons, the soil ammonium contents increased immediately and peaked after fertilization and then decreased rapidly in one week (Fig. 3a). The average soil ammonium content was not significantly different among different soil thicknesses ($P > 0.05$), ranging from 2.5(ST2) to 3.2(ST3) mg N kg^{-1} for the wheat season and from 1.3(ST5) to 1.7(ST3) mg N kg^{-1} for the maize season. After fertilization, the soil nitrate contents increased gradually over the first two months in the wheat season and the first month in the maize season, then decreased and reached the lowest level when the crop was harvested (Fig. 3b). The average soil nitrate contents ranged from 52.3(ST1) to 74.1(ST3) mg N kg^{-1} for the wheat season, and these values were approximately three times higher than those for the maize season (17.0 mg N kg^{-1} for ST1 to 22.6 mg N kg^{-1} for ST3). The average soil nitrate contents for both the wheat and maize seasons were not significantly different among the soil thicknesses ($P > 0.05$).

Table 1
Annual cumulative discharge, NO_3^--N concentration and N loss through surface runoff and leaching.

Treatment	Discharge (mm)				N concentration (mg L^{-1})				N loss (kg N ha^{-1})			
					Surface runoff		Leaching water					
	Total runoff*	Surface runoff	Leaching water	Ratio (%)∮	TN	NO_3^--N	TN	NO_3^--N	Total N loss**	TN leaching	NO_3^--N leaching	Ratio (%)§
ST1	68.4 ± 5.1a¤	6.4 ± 1.0a	61.9 ± 5.4a	90.6	4.73 ± 0.60a	1.24 ± 0.13a	33.61 ± 1.04a	29.80 ± 0.86a	21.09 ± 1.54a	20.79 ± 1.56a	18.41 ± 1.07a	87.3
ST2	51.9 ± 1.6b	4.5 ± 0.3ab	47.5 ± 1.6b	91.4	4.25 ± 0.43a	0.78 ± 0.10c	27.19 ± 1.83b	23.77 ± 1.14b	13.08 ± 0.79b	12.89 ± 0.79b	11.27 ± 0.56b	86.2
ST3	22.0 ± 2.4c	2.6 ± 0.2bc	19.3 ± 2.2c	88.0	4.26 ± 0.78a	0.75 ± 0.18c	28.60 ± 1.70b	25.58 ± 0.72b	5.61 ± 0.36c	5.50 ± 0.36c	4.93 ± 0.45c	88.0
ST4	18.1 ± 0.2cd	2.1 ± 0.2c	16.0 ± 0.1cd	88.6	4.44 ± 0.24a	1.10 ± 0.05ab	21.22 ± 1.71c	19.05 ± 1.93c	3.49 ± 0.27cd	3.40 ± 0.29cd	3.05 ± 0.32cd	87.4
ST5	11.2 ± 0.6d	1.7 ± 0.2c	9.4 ± 0.8d	84.4	4.19 ± 0.50a	1.00 ± 0.07ab	19.96 ± 1.02c	17.66 ± 0.42c	1.96 ± 0.22d	1.89 ± 0.24d	1.66 ± 0.12d	84.7

Note: Treatments ST1, ST2, ST3, ST4 and ST5 represent plots with soil thicknesses of 20, 40, 60, 80 and 100 cm, respectively. * Total runoff is annual cumulative runoff discharges including both surface runoff and leaching water. ** Total N loss is the amount of total nitrogen loss via both surface runoff and leaching. ∮ Ratio of leaching discharge to total runoff. § Ratio of NO_3^--N leaching loss to total N loss. ¤ Mean ± SD; the different lowercase letters indicate significant differences ($P < 0.05$, LSD) under different soil thicknesses.

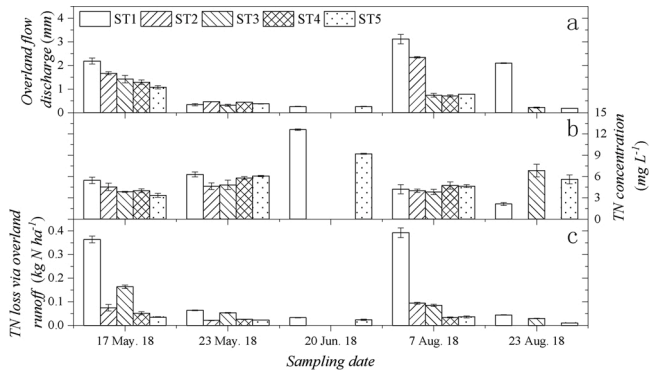

Fig. 4. Seasonal variations in overland runoff (**a**), TN concentrations of overland runoff (**b**) and TN loss via overland runoff (**c**) during October2017-September 2018.
Note: Treatments ST1, ST2, ST3, ST4 and ST5 represent plots with soil thicknesses of 20, 40, 60, 80 and 100 cm, respectively. TN represents total nitrogen. Error bars represent the standard errors of three replicates.

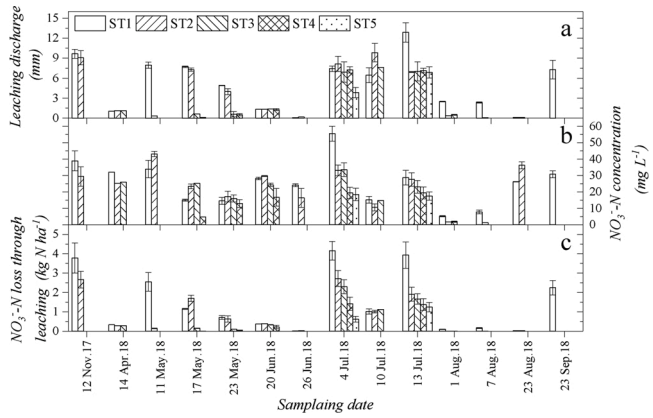

Fig. 5. Seasonal variations in leaching water(**a**), NO_3^--N concentrations of leaching water (**b**) and NO_3^--N loss through leaching(**c**) during October2017-September 2018.
Note: Treatments ST1, ST2, ST3, ST4 and ST5 represent plots with soil thicknesses of 20, 40, 60, 80 and 100 cm, respectively. Error bars represent the standard errors of three replicates.

3.3. N loss pathway and loading

3.3.1. Discharge of surface runoff and leaching water

The annual cumulative total discharges were in the range of 11.2 ± 0.6–68.4 ± 5.1 mm following the sequence, ST1 > ST2 > ST3 > ST4 > ST5, with significant differences among different soil thicknesses ($P < 0.05$) (Table 1). The annual cumulative surface runoff discharges ranged from 1.7 ± 0.2–6.4 ± 1.0 mm, with significant differences among treatments ($P < 0.05$) (Table 1). The annual cumulative leaching discharges were significantly different among soil thickness treatments ($P < 0.05$), ranging between 9.4 ± 0.8 and 61.9 ± 5.4 mm, accounting for more than 84 % of the total runoff (Table 1). Fig. 4a shows that only 5 surface runoff events were monitored for all treatments, while 14, 13, 8, 5 and 2 leaching events were recorded for ST1, ST2, ST3, ST4 and ST5, respectively (Fig. 5a). The leaching frequency was obviously higher than the surface runoff during the rotation year (October 2017-September 2018), suggesting that leaching was the dominant pathway of water loss from sloping cropland. Soil thickness did affect the total discharge volumes (especially the leaching discharge) and governs the runoff response, indicating the substantial contribution of leaching to the total discharge and water conservation capacity of different soil thicknesses.

Table 2
Crop productivity and N uptake under different soil thicknesses (October 2017-September 2018).

Treatments	Winter wheat					Summer maize				
	Yield	Aboveground biomass	Belowground biomass	Harvest index	N harvest	Yield	Aboveground biomass	Belowground biomass	Harvest index	N harvest
	Mg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}		kg N ha^{-1}	Mg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}		kg N ha^{-1}
ST1	1.8 ± 0.1b¤	3.6 ± 0.1b	0.4 ± 0.1d	0.46	52.3 ± 3.8b	0.5 ± 0.1c	5.1 ± 0.3d	0.8 ± 0.1bc	0.11	65.6 ± 10.1d
ST2	2.5 ± 0.1ab	4.8 ± 0.1a	0.4 ± 0.1 cd	0.48	65.1 ± 4.6ab	0.7 ± 0.1c	6.5 ± 0.3c	0.8 ± 0.1ab	0.12	83.4 ± 7.6c
ST3	2.9 ± 0.2a	5.0 ± 0.1a	0.5 ± 0.1bc	0.52	70.5 ± 7.7a	3.6 ± 0.5b	9.3 ± 0.6b	0.9 ± 0.1ab	0.39	102.6 ± 6.6b
ST4	2.9 ± 0.2a	5.0 ± 0.2a	0.5 ± 0.1ab	0.52	70.5 ± 3.0a	5.4 ± 0.3a	11.7 ± 0.2a	0.9 ± 0.1a	0.46	122.1 ± 5.8a
ST5	3.1 ± 0.3a	5.0 ± 0.4a	0.6 ± 0.1a	0.55	73.9 ± 10.2a	5.5 ± 0.4a	11.7 ± 0.4a	0.9 ± 0.1a	0.47	123.9 ± 3.1a

Note: Treatments ST1, ST2, ST3, ST4 and ST5 represent plots with soil thicknesses of 20, 40, 60, 80 and 100 cm, respectively. ¤ Mean ± SD; the different lowercase letters indicate significant differences ($P < 0.05$, LSD) among the soil thickness treatments.

3.3.2. *N concentration and loss loading of surface runoff and leaching*

The TN concentrations of the surface runoff from different plots varied seasonally, with a range of 2.12–12.61 mg L^{-1} per event (Fig. 4b), while the mean TN concentrations of the whole rotation year (October 2017 to September 2018) ranged between 4.19 and 4.73 mg L^{-1}, without significant differences among the soil thicknesses (Table 1). The mean NO_3^--N concentrations of the surface runoff only ranged from 0.75 to 1.24 mg L^{-1} and accounted for less than 27 % of the TN concentrations (Table 1). The mean TN concentrations of leaching water were in the range of 19.96–33.61 mg L^{-1}, with significant differences among the treatments ($P < 0.05$) (Table 1). The NO_3^--N concentrations in the leaching water from different plots fluctuated during the rotation, ranging from 1.27 to 55.50 mg L^{-1} per event, with high values observed from May to August (Fig. 5b). The mean NO_3^--N concentrations of leaching water ranged from 17.66 to 29.80 mg L^{-1} among the treatments, accounting for more than 87 % of the TN concentration (Table 1).

The seasonal change patterns of both TN loss via surface runoff and NO_3^--N leaching loadings (Figs. 4c and 5 c, respectively) were similar to those of surface runoff discharge and leaching discharge, respectively (Figs. 4a and 5 a), as discharge was crucial to N loss loadings via runoff and leaching. Across all soil thickness treatments, the TN loss loadings through surface runoff and leaching of the whole rotation year (October 2017- September 2018) ranged from 1.96 to 21.09 kg N ha^{-1} and significantly decreased in the following sequence: ST1 > ST2 > ST3 > ST4 > ST5 ($P < 0.05$) (Table 1). Similarly, the TN loss loadings through leaching significantly decreased as soil thickness increased (ST1 > ST2 > ST3 > ST4 > ST5, $P < 0.05$), ranging between 1.89 and 20.79 kg N ha^{-1} (Table 1). The NO_3^--N leaching loadings for ST1 to ST5 were 18.41, 11.27, 4.93, 3.05 and 1.66 kg N ha^{-1}, respectively, accounting for more than 84 % of the N loss loadings by hydrological processes (both surface runoff and leaching). The results showed that NO_3^--N leaching could dominate the N loss loadings from Regosol cropland. In addition, soil thickness could be a key regulating factor of N loss loadings via runoff, with significant differences in NO_3^--N leaching loadings among the treatments (ST1 > ST2> ST3 > ST4 > ST5, $P < 0.05$).

3.4. *Crop productivity and N uptake under different soil thickness*

The crop yield, biomass and N uptake values during the wheat and maize seasons are summarized in Table 2. The wheat grain yields for ST1, ST2, ST3, ST4 and ST5 were 1.8 ± 0.1, 2.5 ± 0.1, 2.9 ± 0.2, 2.9 ± 0.2 and 3.1 ± 0.3 Mg ha^{-1}, respectively. The maize grain yields for the respective treatments were 0.5 ± 0.1, 0.7 ± 0.1, 3.6 ± 0.5, 5.4 ± 0.3 and 5.5 ± 0.4 Mg ha^{-1}, respectively. The wheat and maize grain yields of ST3, ST4, and ST5 were significantly higher ($P < 0.05$) than those of ST1, while no significant differences were found in ST1 and ST2. The results revealed that a soil thickness of 60 cm or thicker is optimum to obtain higher yields. The results of the statistical analysis of the aboveground biomass, belowground biomass and N uptake were similar. The aboveground biomass, belowground biomass and N harvest of wheat and maize were not significantly different between ST4 and ST5, whereas these values were significantly higher ($P < 0.05$) than those for ST1. Crop biomass production and N uptake appeared to be sensitive to soil thickness and increased as soil thickness increased.

4. Discussion

4.1. *Impact of soil thickness on water conservation*

With a unique dual rock-soil structure (Xiong and Li, 1986), the Regosol region could be a regulated area with a high incidence of N leaching on farmland due to water loss. It has been reported that the soil water retention capacity is mainly affected by the soil conditions (Li et al., 2009). Of which, the water retention capacity of a soil profile is mainly determined by the soil thickness (Geroy et al., 2011). The daily average soil moisture was significantly different among the treatments ($P < 0.05$) (Fig. 1b), suggesting a positive effect of the soil-layer thickness on soil water conservation. This result was consistent with the result of Zhu et al. (2009b) and led us to postulate a mechanism to accommodate water conservation within the soil system. More soil water would be retained if the soil thickness is larger due to the greater storage capacity. The capacity of the soil to retain water is affected by the stresses imposed by gravitational drainage (Geroy et al., 2011). In this study, the total discharge of leaching significantly decreased as the soil

Table 3
Linear regression analysis of the effects of soil thickness on discharge and N concentration of surface runoff and leaching.

			Regression functions	R^2	P
Discharge	Total runoff		D(TR) = 78.78631+(-0.74136)*ST	0.8769	<0.05
	Surface runoff		D(SR) = 7.00511+(-0.05897)*ST	0.86646	<0.05
	Leaching water		D(LW) = 71.78121+(-0.68239)*ST	0.87588	<0.05
N concentration	Surface runoff	TN	C(SRTN) = 4.64661+(-0.00452)*ST	0.22911	>0.05
		NO_3^--N	C(SRNN) = 1.02332+(-7.9433E-4)*ST	−0.31392	>0.05
	Leaching water	TN	C(LWTN) = 36.09798+(-0.16632)*ST	0.84377	<0.05
		NO_3^--N	C(LWTN) = 31.87209+(-0.14504)*ST	0.81697	<0.05

Note: D and C represent discharge and N concentration, respectively. TR, SR and LW represent total runoff, surface runoff and leaching water, respectively. SRTN and SRNN represent TN of surface runoff and NN of surface runoff, respectively. LWTN and LWNN represent TN of leaching water and NN of leaching water, respectively. ST represents soil thickness.

Table 4
Soil nitrate stock (kg N ha^{-1}) in the soil profile.

	Winter wheat					Summer maize				
	Nitrate stock	Nitrate stock distribution (kg N ha^{-1})				Nitrate stock	Nitrate stock distribution (kg N ha^{-1})			
Treatments		0~20	20~40	40~60	Sub-60		0~20	20~40	40~60	Sub-60
ST1	38.67 ± 4.23d	38.67 ± 4.23b	—	—	—	9.70 ± 0.43d	9.70 ± 0.43a	—	—	—
ST2	80.10 ± 12.69c	36.71 ± 4.23b	43.39 ± 8.60	—	—	13.37 ± 0.65d	10.21 ± 0.17a	3.16 ± 0.54	—	—
ST3	120.60 ± 8.39b	45.79 ± 7.06ab	54.35 ± 2.42	20.45 ± 4.10	—	28.27 ± 2.58c	13.53 ± 2.12a	9.18 ± 2.66	5.55 ± 1.24	—
ST4	134.81 ± 6.57b	51.59 ± 3.14ab	49.91 ± 2.95	20.90 ± 6.27	12.41 ± 4.21	38.75 ± 1.47b	12.58 ± 1.75a	7.93 ± 2.18	11.13 ± 1.36	7.11 ± 0.68
ST5	183.97 ± 6.93a	55.00 ± 3.24a	56.54 ± 4.48	31.04 ± 4.14	41.38 ± 8.38	46.76 ± 4.22a	11.30 ± 0.87a	7.34 ± 1.37	12.73 ± 2.36	15.39 ± 0.58

Note: Treatments ST1, ST2, ST3, ST4 and ST5 represent plots with soil thicknesses of 20, 40, 60, 80 and 100 cm, respectively. Soil nitrate stock was defined as soil NO_3^--N reserve after the harvest of each season (both winter wheat and summer maize season), respectively. ¤ Mean ± SD; the different lowercase letters indicate significant differences ($P < 0.05$, LSD) among the soil thickness treatments.

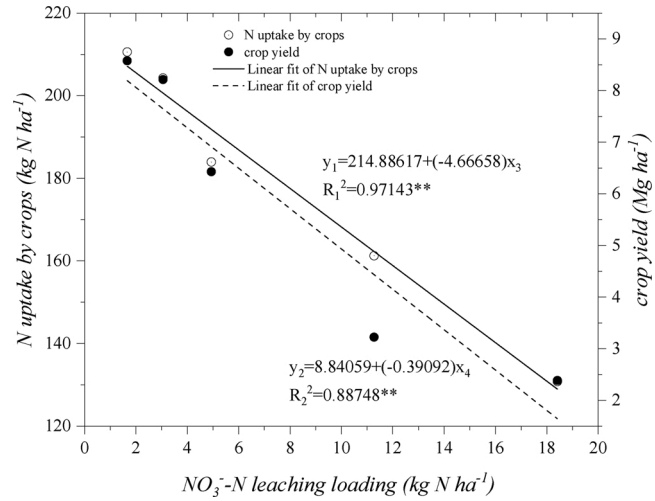

Fig. 6. Linear function and fitting line of nitrogen uptake by crops and annual crop yields based on annual NO_3^--N leaching loading.
Note: N uptake by crops and crop yields were defined as N uptake by crops and crop yields of an entire rotation (October 2017-September 2018). **Regression significant at $P < 0.05$.

thickness increased ($P < 0.05$) (Table 1). Therefore, soil thickness can be an effective proxy for indicating the ability of Regosol sloping cropland to retain water.

4.2. Factor influenced by soil thickness and its contribution

Linear regression analysis of the effects of soil thickness on discharge and N concentration of surface runoff and leaching was shown in Table 3. The discharge influenced by soil thickness was the main factor for both surface runoff and leaching water ($R^2 = 0.86646$ and 0.87588, respectively, $P < 0.05$). In addition, N concentration of leaching water was also an important factor influenced by soil thickness ($R^2 > 0.8$, $P < 0.05$). Generally, the discharge is more affected by soil thickness compared to N concentration, while leaching is more affected by soil thickness than surface runoff.

4.3. Soil nitrate retention in response to soil thickness

Soil N reserves may reflect soil fertility to a certain extent (Wang et al., 2019b). In this study, Nitrate stocks were measured to estimate the soil nitrate reservation ability. Nitrate was the main form of mineral N in the tested soils, and its content in the soil generally showed no significant difference among the five treatments (Fig. 3), whereas the nitrate stock of the entire soil profile was positively correlated with the soil thickness (ST5 > ST4 > ST3 > ST2 > ST1, $P < 0.05$) (Table 4). These results indicate the significance of thicker soil in improving the soil nitrate reserves.

Combined with the input and main output ways of nitrogen, it can be seen that the soil nitrogen storage capacity (Table 4), the absorption and utilization degree of nitrogen by crops (Table 2) and the nitrogen loss by hydrology ways (Table 1) are all significantly related to soil layer thickness. Thicker soil tends to reserve more N with lower negative impacts on the environment by reducing N loads through hydrological ways (especially leaching). Therefore, crop (especially maize) can achieve higher yields with thicker soil thickness due to N uptake from deeper soil layer.

4.4. NO_3^--N leaching loss in relation to crop yield

The linear relationships between N uptake by crop and crop yields for NO_3^--N leaching loadings are shown in Fig. 6. N uptake by crops and

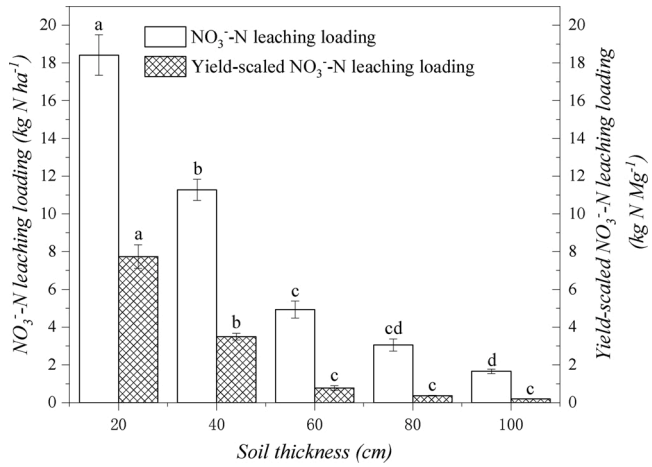

Fig. 7. Yield-scaled nitrate leaching loading in relation to soil thickness. Note: The vertical bars represent the standard errors of three replicates. The different lowercase letters indicate significant differences ($P < 0.05$, LSD) under different soil thicknesses.

crop yields tended to increase as the soil thickness increased (Table 2), corresponding to the decreased NO_3^--N leaching loadings (Fig. 6). NO_3^--N leaching can be regulated by soil water conservation and NO_3^--N retention, which are positively correlated with the soil thickness (Fig. 1b and Table 3). These results indicate that N leaching loss can be alleviated by reducing the discharge of percolated water, which has also been evidenced by Liang et al. (2019). Yan et al. (2019) reported that soil water storage could positively affect soil N retention, which may explain why both soil moisture and N stock share the same change pattern as the soil thickness increases. Relatively thick soil prolongs the retainment of N in field, thus promoting N uptake by crops and leading to a higher crop yield. Overall, a thicker soil layer was conducive to N uptake and crop growth and responded to the increase in crop yields.

Because soil with a thickness of 20−40 cm could not retain enough water for crop growth needs, the total crop biomass and yields of the 20−40 cm thick soil were obviously lower than those of the 60−100 cm thick soil ($P < 0.05$). As described by Fu et al. (2011), soil thickness might was a principle factor causing redistribution of rainfall or irrigation water. Shallow soils reflected weaker capacity in maintaining soil water as compared to thicker soils. Hydro-pedological properties may be the dominant reasons for different hydrological phenomenon among soils with different soil thickness (Lin, 2010). In addition, NO_3^--N leaching loadings in the 20−40 cm thick soil were obviously higher than those in the 60−100 cm thick soil ($P < 0.05$) (Fig. 7). Yield-scaled NO_3^--N leaching describes the responses of cumulative nitrate leaching loadings to crop yields, which is an integrated metric that addresses the dual goals of preventing water pollution and ensuring crop yields (Zhou et al., 2014). In this study, the yield-scaled NO_3^--N leaching loadings of the 60, 80 and 100 cm treatments were also significantly lower than those of the 20 and 40 cm treatments ($P < 0.05$) (Fig. 7). The results reveal that the relatively thick soil can significantly reduce the yield-scaled NO_3^--N leaching loadings. The soil thickness of 60 cm can be critical for crop growth needs and a comprehensive response (crop aboveground biomass, crop root biomass, and crop yields) due to the capacity of the soil to ensure high crop yields under climatic and edaphic constraints, and this soil thickness can mitigate environmental risks by reducing nitrate leaching losses.

Therefore, according to the results of this study, some suggestions on the reclamation and utilization of degraded sloping croplands can be obtained. The soil thickness of shallow sloping croplands requires to be reclaimed to at least 60 cm in order to ensure water conservation, control nitrogen retention and maintain crop yields, thus reducing N pollution. If the soil thickness of degraded croplands cannot be reclaimed to 60 cm, the land use patterns might be recommended as returning croplands to grassland or orchard with reducing fertilization to control non-point source pollution.

5. Conclusions

This study highlights the importance of the soil thickness for crop growth, water utilization and nitrate leaching in croplands in hilly and mountainous areas suffered from soil erosion. Significant differences were found in the crop yield, soil moisture, N uptake, and N leaching values among different soil thicknesses ($P < 0.05$). Surface runoff and leaching discharge significantly decreased as soil thickness increased (ST5 < ST4 < ST3 < ST2 < ST1, $P < 0.05$). Crop yield was positively correlated with soil thickness (ST5 > ST4 > ST3 > ST2 > ST1, $P < 0.05$), while NO_3^--N leaching loadings and yield-scaled NO_3^--N leaching loadings were significantly negatively correlated with soil thickness (ST5 < ST4 < ST3 < ST2 < ST1, $P < 0.05$). Therefore, soil thickness is a critical factor for soil water and nutrient retention and soil productivity in sloping cropland that is experiencing soil erosion. We identified a critical soil thickness value of 60 cm, which can be expected to maintain crop productivity and mitigate nitrate losses from Regosol sloping croplands in the upper YRB. A soil thickness of 60 cm is recommended as a threshold to support the land reclamation of degraded croplands due to severe soil erosion. If degraded land cannot be reclaimed to meet a soil-layer thickness of 60 cm, those degraded sloping cropland might be replaced by permanent cover such as grassland and orchard with less fertilization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Financial support for this research was provided by the National Key R&D Program (Grant No. 2016YFD0200309-7). The authors gratefully acknowledge the staff of the Yanting Agro-Ecological Station of Purple Soil for their support during the field experiments.

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