Residue cover effects on soil erosion and the infiltration in black soil under simulated rainfall experiments

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9 **Abstract**

10 Residue cover is widely used in the Northeastern China Black Soil Region
11 for soil erosion control due to the large annual production of crop residues.
12 Quantitative evaluations of the residue cover effects on preventing soil loss
13 and on the cumulative infiltration amount are thus desirable. Herein, rainfall
14 simulation experiments were conducted using simulators and soil flumes to
15 study the effects of residue cover on soil erosion and infiltration under various
16 rainfall events. Laboratory experiments were designed utilizing five levels of
17 residue cover (bare, 15%, 35%, 55% and 75%), four rainfall intensities
18 (30mm/h, 60mm/h, 90mm/h and 120mm/h), two soil moistures (dry and wet
19 run) and a fixed slope of 7%.

20 The results indicated that residue cover strongly affects runoff, soil loss
21 and infiltration. Equations for predicting the soil loss ratio and infiltration ratio
22 (the ratio of residue cover soil to bare soil) are herein proposed based on
23 nonlinear curve regression. An empirical approach presented as the infiltration
24 ratios multiplied Philip's equation derived from bare soil was established for
25 estimating the cumulative infiltration amounts under various residue covers.
26 The equation was demonstrated to be suitable for infiltration prediction for
27 black soil by the root mean square error value and 1:1 line method. In addition,
28 the relationship between the residue cover and biomass (or yield) of corn
29 residues was provided in order to enable accurate measurement of the residue
30 coverage. These derived equations could be used for soil erosion and

31 infiltration prediction under no-till and residue cover management conditions in
32 the black soil region.

33

34 Keywords: residue cover, soil loss ratio, infiltration ratio, cumulative infiltration
35 amounts prediction.

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1. Introduction

Black soil is widely distributed in the northeastern area of China where it supports 17.1% of the total grain production in China, including 33.5%, 55.7% and 9.6% of the corn, soybean and rice production, respectively (Duan et al., 2010; Liu et al., 2011). However, over-exploitation and unsustainable land use have led to substantial soil loss and soil productivity reduction since the 1950s (Fan et al., 2004; Liu et al., 2008). In addition, the topography of the black soil region is characterized by gentle, long slopes (rolling hills), which lead to large topsoil erosion and deposition at the toe of slopes but limited sediment transport towards the watershed outlet (Xu et al., 2010; Liu et al., 2015). This low sediment transport to the waterways distracts interest away from the awareness of protecting soil erosion. However, according to large annual production of crop residues, residue cover has long been one of the most widely applied soil conservation practices in this dryland cultivation area since they were no longer used as fuels here in the 1990s (Yang et al., 2003). Residue cover is so widely applied as it can prevent raindrop splashing, reduce runoff velocity, increase infiltration, bind soil crusting and maintain the roughness of the soil surface (Brown and Norton, 1994; Lal, 1998; Wilson et al., 2004).

The soil erosion prediction in the presence of residue cover is mainly based on the calculation of cropping-management factor (the so-called C factor). The C factor is the ratio between soil loss from land cropped under

specified conditions and the corresponding loss from clean-tilled, continuous fallow in the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978). Residue cover is one of the most important components in the C factor and has its appropriate equations for the soil loss prediction purpose in the revised USLE (RUSLE) (Renard et al., 1997). Previous studies have reported the appropriate C factor values under the residue cover management in the black soil region. Zhang et al. (1993) proposed C factor values for five major crops in the range of 0.09 - 0.48 for four crop stage periods by observing 21 plots of land for four years. Lin et al. (1997) gave C values for continuous corn-soybean rotation in the range of 0.47 - 0.53 based on observation data collected over eleven years. However, no studies have been conducted concerning quantitative prediction equations of residue cover effects on soil loss in the black soil region to our knowledge. A formulation for the residue cover effect on soil loss is necessary in the black soil region for prediction purposes. Accurate measurement of the residue cover is necessary for an accurate prediction of soil erosion.

An indirect method for the measurement is to establish relationships between the residue cover and other variables for quantitative deduction. Gregory (1982) recommended an exponential function for estimating the residue cover fraction from the residue biomass. In recent research, the residue cover fraction has been estimated using long-term crop yields (Huffman et al., 2006) and the straw-to-grain ratio method (Bolinder et al.,

2007). It is necessary to develop an appropriate relationship between residue cover and residue biomass for accurate measurement of coverage in the black soil region.

Many studies have demonstrated the positive effect of residue cover on soil infiltration (Jin et al., 2009; Lang and Mallett, 1984; Mailapalli et al., 2013). However, few studies have been conducted with an aim to establish a special equation for predicting the effect of residue cover on the cumulative infiltration amounts. Morin and Benyamini (1977) assumed infiltration rate as a function of the cumulative rainfall amounts by studying the infiltration rate through bare and mulched soil under different rainfall intensities. Corradini et al. (2000) developed a semi-analytical model for local infiltration-redistribution-reinfiltration in a two-layered soil profile in crusted soil. The model indicated that the more permeable upper layer was an appropriate way to take into account the effect of a vegetated layer. Morbidelli et al. (2014) relied on the hypothesis of the aforementioned Corradini et al. (2000) model and provided a new conceptual infiltration-redistribution model to predict the soil moisture content at a local scale in soils with vegetation under natural conditions. The effect of vegetation was represented by a fictitious soil vertical profile with a more permeable upper layer in the model calibration. The most widely used infiltration models, such as the physically based models (Green and Ampt, 1911; Philip, 1957) and empirical relations models (Horton, 1933), mostly focus on simulations of the physical process based on bare soil. Nevertheless,

once the infiltration rate of bare soil is obtained by the given model, the infiltration of soil with residue cover can be predicted using a ratio of infiltration amounts from the residue cover soil and the bare soil. It is thus necessary to establish a residue cover factor (RCF) on infiltration amounts for prediction purposes.

In the present study, black soil was selected to study the effects of various residue covers on soil loss and infiltration in rainfall simulation experiments. The aims of the present study were: (1) to establish an equation for residue cover (RC) by using the residue weights; (2) to establish equations for residue cover factors for predicting soil loss (RCFs) and infiltration (RCFi); (3) to develop an empirical method for predicting cumulative infiltration amounts under residue conditions by combining the residue cover factor and Philip's equation.

2. Material and methods

2.1 Design of the rainfall experiments

Black soil (classified as Udic Isohumisols in the Chinese Soil Taxonomy, or Udic Argiboroll in the US Soil Taxonomy) (Gong et al., 1999) was selected for experiments with four simulated rainfall intensities (30 mm/h, 60 mm/h, 90 mm/h and 120 mm/h) under bare soil and under four corn residue covers. The choice of the rainfall intensities referred to the rainfall return periods of the northeastern part of China according to the "Chinese Rainstorm Statistic Parameter Atlas" (2006). The maximum rainfall within 1 hour and 6 hours is 30

mm and 60 mm separately in multi-year average precipitation. The maximum rainfall within 1 hour and 6 hours is 90 mm and 120 mm separately in hundred-year storm. Each treatment was carried out in both dry and wet runs with an interval of 24 hours between runs, and each run lasted one hour. The two runs represented the extreme dryness and wetness of the soil moisture in the field. All the treatments were performed twice, in order to assess the reproducibility and precision of the experiments. In total, 80 runs were conducted in the rainfall simulation laboratory of Beijing Normal University, China, in 2014 and 2015.

2.1.1 Rainfall simulator and soil flume

All the experiments were conducted with the spray-nozzle rainfall simulators set at 4 m height above the floor, which produced a controlled rainfall intensity ranging from 20 to 140 mm/h. Each simulator had five Veejet 80100 nozzles with 0.04 MPa water pressure. In each rainfall event the combined use of all simulators was necessary and the rainfall uniformity coefficient was more than 89% (Xie et al., 2008) which was high enough in Sangüesa's research (2010). The distance between two adjacent simulators was 1.5 m and 1.1 m intervals between the two nozzles, so the available rainfall area was $(n-1) \times 1.5 \times 4.4 \text{ m}^2$ under combined use (where n is the number of simulators).

The soil flume was a steel unit, rectangular shaped in the size 2 m × 1 m × 0.35 m (length × width × depth) with a fixed bed slope of 7%. The slope was

determined according to the grade scale of soil erosion intensity standard of the experimental field. Two flumes were put together under three rainfall simulators in a vertical direction for each rainfall event according to the size of rainfall simulator and soil flume (Fig. 1). There were four wheels for transportation and a triangle water outlet ahead of the flume for free movement of the runoff and sediment. Black soil of 0.25 m deep was filled in the flume layered, the upper soil layer was 0.1 m deep and the sublayer was 0.15 m deep. They were compacted uniformly to achieve the target soil bulk which was determined by the multiple and stratified sampling method using a soil auger ranged from 1.07- 1.25 g/cm³. The contact surface of the two layers was roughened by reference to the Zhao's (2014) research before adding the next layer in order to reduce soil stratification which could affect infiltration. The soil surface was scraped plain with a wooden board for reducing the influence of roughness. The lower boundary of the soil flume is closed and the soil water become saturated with time. The lateral subsurface flow would turn to the runoff form and leave the system after the soil became saturated.

2.1.2 Black soil and corn residues' treatment

The black soil utilized in the experiments was collected from the Jiusan Soil Conservation Station located in the Northeastern China Black Soil Region, and comprised the top 20 cm soil from cultivated land. The bulk density was 1.16 g/cm³, while the organic matter content was 5.0% and the particle size distribution was 32%, 33%, 35% for sand, silt and clay, respectively. The soil

was sun-dried to around 8% volumetric moisture content, as measured by a TDR sensor, for the dry runs. In order to ensure identical initial conditions before each rainfall event, the soils in the flume were removed and then replaced with fresh soil following an established protocol which was consistent with Montenegro's (2013) treatment when they studied the impact of mulching on soil and water dynamics under intermittent simulated rainfall.

Corn straws were used for the experiments. These were fully sun-dried outside, and then shortened to 5 cm each. Each rainfall event used new dry straws except for the wet runs. The water retention of the corn residues was too small to be considered in the calculation.

2.1.3 Residue coverage index design

According to the *"Techniques standard for comprehensive control of soil erosion in the black soil region"* (SL 446 - 2009), five covers of corn residues (bare, 15%, 35%, 55% and 75%) were chosen. The corn residues were manually spread along the flume uniformly with a fixed amount before each rainfall event.

To obtain accurate residue coverage, an object-based image analysis method was used to assess the coverage by using residue weights (Bauer and Strauss, 2013). Several dry weights of corn residues in equal intervals were randomly set in the 2 m² flume, and then the images were taken by a Nikon P7100 digital camera. The coverage was estimated using the supervised classification in ENVI 4.8 software (Fig. 1). The relationship between residue

cover and residue dry weight was regressed based on Gregory's research (Gregory, 1982):

$$RC = 1 - \exp(-\alpha \times B_s) \quad (1)$$

where RC is the percent residue cover, α is the ratio of the area covered by a piece of residue to the mass of that residue (ha/kg) and B_s is the residue dry weight on the surface (kg/ha). The above mentioned covers of 15%, 35%, 55% and 75% and the corresponding residue weights are shown in Table 1.

2.1.4 Measurements during the rainfall events

For each run, the runoff start time was recorded, and the runoff was collected into a bucket and two bottles at intervals of 5 min. The runoff volume was measured from both the bucket and bottles. The sediment was collected in the two bottles and deposited for separating from the runoff, and then weighed after oven-drying at 105 °C for 24 hours. The infiltration amounts were the difference between the rainfall amounts and runoff, while the evaporation and residue retention during rainfall events was neglected.

2.2 Data processing

First, the residue factors for soil loss and infiltration were defined as the ratios of soil loss and infiltration from rainfall events on bare soil to rainfall events on soil with different levels of residue cover, respectively:

$$RCFs = SL_r/SL_b \quad (2)$$

$$RCFi = CI_r/CI_b \quad (3)$$

where $RCFs$ is the residue cover factor for soil loss, $RCFi$ is the residue

cover factor for infiltration. SL_r and SL_b is the measured values (t/hm^2) obtained from each rainfall events of soil loss with residue cover and bare soil. CI_r and CI_b is the cumulative infiltration amounts (mm) with residue cover and bare soil.

Second, the function of $RCFs$ with residue coverage was regressed using:

$$RCFs = \exp(-b \times RC) \quad (4)$$

where $RCFs$ is the residue cover factor for soil loss, RC is the residue cover percent and b is the regression coefficient, which shows the effectiveness of cover in reducing soil loss. Note, the effect of the soil roughness is omitted in the equation. The relationship between $RCFi$ and RC needed to be established by the observed data.

Third, Philip's infiltration model (1957) was used to develop an empirical method for predicting infiltration under residue cover conditions with the combined residue cover factor for infiltration ($RCFi$). The Philip's equation was:

$$i(t) = 0.5St^{-0.5} + aK_s \quad (5)$$

where S is the parameter called sorptivity ($cm/min^{0.5}$) and is mainly determined by the soil moisture (Wang et al. 2010; Dagan and Bresler, 1983; Wang et al. 2015), K_s is the saturated hydraulic conductivity (cm/min) and a is a constant that is generally set as 2/3 (Palange et al, 1982). To determine S and K_s , the bare soil rainfall event data under different rainfall intensities and soil moistures was used for regression.

Furthermore, the infiltration with residue covers could be obtained by

231 multiplying the residue cover factor for infiltration ($RCFi$) and the Philip's
232 equation:

$$i(t)_r = RCFi \times (0.5St^{-0.5} + aK_s)_b \quad (6)$$

233 Finally, the predicted infiltrations for various corn residue covers were
234 compared with the observed infiltration rates to assess the model performance
235 by calculating the root mean square error (RMSE) and using a 1:1 line
236 regression method (one of the T test method, by estimating whether the
237 confidence interval of the slope and intercept of the regressed equation include
238 the number of 1 and 0, respectively. If included, it indicates that there is no
239 difference between the regressed curve and the 1:1 line. It further indicates
240 that there is no difference between the simulated values and observed values).

241 All the data processing and analysis were performed with SPSS 20.0
242 software (IBM, USA) and Origin 8.0 software (OriginLab, USA). The means of
243 two replicates were compared using the least significant difference test at a $p <$
244 0.05 significance level. The functions were regressed by a nonlinear curve or
245 linear fitting techniques.

246 **3 Results and discussions**

247 **3.1 Observed effects of residue cover on runoff and soil loss**

248 Both runoff and soil loss decreased with increasing residue cover, and the
249 residue cover had a more notable effect on reducing soil loss than runoff as
250 expected, which is similar to the Wilson's results (2008) on residue impacts on
251 runoff and soil erosion for different corn plant populations. (Fig.2). The mean

runoff reductions were 30.3%, 27.1%, 56.8% and 72% for the 15%, 35%, 55% and, 75% residue covers compared to bare soil, respectively. The mean soil loss reductions were 41.5%, 58%, 89% and 96% for the 15%, 35%, 55% and 75% residue covers, respectively. When the rainfall intensity was higher, the protection effectiveness of the residues was weakened. The runoff reduction of the 35% residue cover was lower than with 15% cover under high rainfall intensities (i.e. 90 mm/h and 120 mm/h). The reason for this might be that residue amounts of 35% cover had formed a fixed runoff flow path. Although the 35% covering of residues could still play a role in protection and retention compared to bare soil, it might accelerate runoff velocity with a fixed path and induce runoff generation under high rainfall intensities (Meyer et al., 1970).

3.2 Observed effects of residue cover on infiltration

Figure 3 shows that residues covering the soil surface retain the runoff generation and increase the infiltration rates in contrast to the bare slope under various rainfall rates and soil moistures. The formation of a physical crust on the bare soil surface is the main reason (Jin et al., 2008). When the soils are wetted or exposed to rainfall, a thin seal or skin forms as the soils dry after clay dispersion (Yan et al., 2015). Generally, the soil crusts reduce the hydraulic conductivity of the bare soil significantly and decrease the infiltration amounts into the soil consequently, which is even more pronounced under high rainfall intensities (more than 30mm/h) than it is under low rainfall intensities (Bu et al., 2014). Residues covering on the slope surface would weaken the splash

erosion and the crust formation. In Figure 3, the infiltration rates of various covers decreased with time during the rainfall and tended towards a relative steady state at the end of the wet runs. The final infiltration rate (FIR) of bare soil was around 0.21- 0.51 mm/min, the FIR of residue cover soils were around 0.4 - 0.8 mm/min under different rainfall intensities of the wet runs. The antecedent soil moisture and the infiltration rate have a negative relationship which is in accord with the Wangemann's (2000) results.

3.3 Estimate of residue cover factors for predicting soil loss and infiltration

The present paper establishes the relationship between residue cover and residue biomass presenting as the Eq. (1) by using the nonlinear curve fitting method and the α was equal to 0.00024 kg/ha ($R^2 = 0.93$, $p < 0.01$) (Fig. 4). The derived value of α is smaller than the recommended value in RUSLE of 0.00038 ha/kg. The difference might be due to the lack of husks in the residue and weathered leaves after the soil was fully sun-dried which lightened the actual residues weight, like in Gregory's research (1982). The last three points form a plateau when the percent of residue cover was over 70% in Figure 4. It indicated that when the percent cover was less than 70%, the corresponding biomass could be obtained accurately by the regression curve. However, it could not get an exact biomass amount when the percent exceeds 70% as the cover percent changes little even if the biomass increases a lot.

The $RCFs$ and $RCFi$ values were determined during the experiments

with different residue covers and rainfall intensities (Table 2). The b value in Eq. (4) was 0.03 (R^2 was 0.86, $p < 0.01$) (Fig.5) and the established relationship between $RCFi$ and RC was,

$$RCFi = 0.94 \times RC + 1 \quad (7)$$

(R^2 was 0.5, $p < 0.01$) (Fig.5).

The former studies have demonstrated that soil loss decreases exponentially as the percentage of residue cover increases (Jin et al., 2008; Kosmas et al., 1997). The b value is an important parameter in the exponential function and expresses the effectiveness of the residue cover to reduce soil loss according to RUSLE. It varies in different cases, such as with different types of residues and field managements (Thorburn et al., 2001). Jennings and Jarrett (1985) reported the effectiveness of eleven types of mulch on reducing soil loss under rainfall simulation experiments. Laflen and Colvin (1981) suggested the b value was based on the soil characteristics and/or slopes and recommended experienced values in the range of 0.03 to 0.07 under some special conditions. Brenneman and Laflen (1982) suggested that the effectiveness of surface cover was associated with the shape of the mulch, and that large and long mulch were more efficient in soil erosion reduction than small and flat pieces. Our study conducted the rainfall experiments and obtained an appropriate b value using the major crop corn straws under no-till and residue cover management conditions. Therefore, the obtained b value was applicable in the same treatment.

3.4 Predicting the infiltration rate under various residue covers

In order to eliminate the effect of rainfall intensity and soil moisture, infiltration rate data from bare soil for four rainfall intensity events were collected together and averaged. The time domain was sliced into 12 time steps, with time steps of 5 minutes for each rainfall event. The derived S value was 3.2 and the K_s was 0.29 ($R^2=0.51$, $p < 0.01$). Hence, the empirical equation for infiltration with residue covers was established. To test the proposed equation, the simulated infiltration rate was compared with the observed values (Fig. 6). The RMSE value under different residue cover, 15%, 35%, 55% and 75%, was 0.006, 0.009, 0.011 and 0.031 mm/min, respectively. All the values were small. The 95% confidence interval of the slope and intercept of the regression equation derived from the simulated and measured was respectively (0.99, 1.38) and (-0.29, 0.00) (lower, upper). The intervals include the number of 1 and 0, so there was no significant difference between the regression line and the 1:1 line (Fig. 6). These results indicate that the equation could estimate the infiltration rate well for black soil with different residue covers.

Philip's equation is used to estimate bare black soil infiltration rate but requires an extremely high accuracy of the hydraulic parameters (Chahinian et al., 2003). However, the paper used the average values of different rainfall events and the same time steps for regression. Thus the obtained results may be changed due to the parametric uncertainty under different treatments

(Wang et al., 2015). Both the 1:1 line result and the RMSE values demonstrated that the derived equation, which is a product of the residue cover factor equation and Philip's equation, was quite more appropriate for the prediction of cumulative infiltration amounts than the prediction of infiltration rates as the total amounts could neglect the infiltration process and the changes of the parameters. There are some outliers, as can be seen in Fig. 6. These are characterized by high values of infiltration rate and high residue cover. This might be explained by the fact that the average values of different rainfall events were used for regression. An increase in residue cover leads to an increase in the cumulative infiltration. However, the effect of the high residue cover on soil infiltration decreases gradually as the rainfall continues. The infiltration rate late in a rainfall event is much smaller than that in the beginning of the rainfall event. The $RCFi$, as an average value for rainfall events, would overestimate infiltration for the later rainfall process when the effects of residue cover on infiltration decrease. Thus the derived equation is more accurate for predicting cumulative infiltration rather than the infiltration rate during the rainfall process.

4. Conclusion

The effects of residue cover on soil erosion and infiltration for black soil were estimated based on a ratio form ($RCFs$ and $RCFi$, respectively) through an analysis involving laboratory experiments with artificial rainfall and two soil flumes. A method for estimating the residue cover was developed by using the

residue biomass weight. An experienced method was developed for predicting the accumulated infiltration amount by using the product of the $RCFi$ and Philip's equation for bare soil. Comparisons of the simulated and observed values were tested via the RMSE value and 1:1 line method and the results proved the feasibility of the prediction method. The derived equation establishes the relationship between the residue cover management and the black soil's accumulated infiltration amounts. Once the residue cover is known, the corresponding accumulated amounts can be obtained.

The paper considered different levels of rainfall intensity, antecedent soil moisture and residue coverage. However, the effect of changing slope on infiltration and soil loss with different residue coverage requires further experiments to assess the slope influence. The present study established equations for the effect of residue cover on soil infiltration. Moreover, the residue cover factor $RCFi$ for the cumulative infiltration is proposed and we developed its linear regression equation for the residue cover. Whether the derived equation is suitable for other crop residues and managements should be studied further.

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529

Table1 The designed residue cover and the corresponding biomass weight.

Residue cover (%)	15	35	55	75
Residue weight (t/ha)	0.7	1.8	3.3	5.8

Table 2 Values of the RCFs and RCFi under various residue covers (from 15% to 75%) during the experiments with different rainfall intensities.

RI(mm/h)	RCFs				RCFi			
	15%	35%	55%	75%	15%	35%	55%	75%
30mm/h	0.32	0.20	0.00	0.00	1.23	1.25	1.35	1.34
60mm/h	0.70	0.48	0.10	0.03	1.26	1.34	1.84	1.99
90mm/h	0.64	0.64	0.12	0.08	1.31	1.01	1.50	1.96
120mm/h	0.85	0.57	0.22	0.08	1.19	1.13	1.43	1.75

Figure captions

Fig. 1 Laboratory experiments setup.

Fig. 2 Observed runoff (a) and soil loss (b) obtained with various residue covers during the experiments with four rainfall intensities.

Fig. 3 Observed infiltration rates during the laboratory experiments with various residue covers (from 0% to 75%) under different rainfall rates.

Fig. 4 Relationship between the residue biomass, B_s , and residue cover, RC: experimental points and regression curve.

Fig. 5 Relationships between the residue cover factors for predicting soil loss, RCFs (a), and infiltration, RCFi (b), and the residue cover, RC: experimental points and regression curve.

Fig. 6 Comparison of the observed and simulated average infiltration rates obtained with different residue covers (15%, 35%, 55% and 75%).

Laboratory experiments setup

The control system of the simulators

Different covers of corn residue used in the experiments: a) 15% cover, b) 35% cover, c) 55% cover, d) 75% cover, defined according to the classification by the ENVI 4.8 software.

FIG2.EPS

FIG3.EPS

FIG4.EPS

FIG5.EPS

FIG6.EPS