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Impacts of mollic epipedon thickness and overloaded sediment deposition on corn yield in the Chinese Mollisol region

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ABSTRACT

Topsoil loss and overloaded sediment deposition profoundly influence soil productivity. Understanding the changes in crop yield with the decrease of topsoil thickness and the increase of sediment deposition depth is crucial to elucidate the effects of soil erosion and deposition on soil productivity. However, little information is available concerning how mollic epipedon thickness and overloaded sediment deposition affect crop yield in the Mollisol region of Northeast China. The objectives of this study were to quantify the effects of mollic epipedon thickness and sediment deposition depth on corn (*Zea mays L.*) yield in the Mollisol region of Northeast China. Simulated field experiments, including seven mollic epipedon thicknesses (0, 5, 10, 15, 20, 40 and 60 cm) and five sediment deposition depths (0, 7.5, 15, 22.5 and 30 cm) were conducted in two independent experiments, respectively. The results showed that corn yield reduced as mollic epipedon thickness decreased, and corn yield reduced more sharply when mollic epipedon thickness was less than 20 cm. Compared with the control treatment with 60 cm mollic epipedon, the corn yield reductions were 8.2%, 15.8%, 21.3% and 24.2%, respectively, for the treatments with 15, 10, 5 and 0 cm mollic epipedon. Moreover, the negative impacts of overloaded sediment deposition at the corn seeding stage on corn yield were also analysed in this study. The corn yield significantly decreased as sediment deposition depth increased. Compared with the control treatment without sediment deposition, the corn yield was decreased by 31.7% for the treatment with 30 cm sediment deposition depth. Additionally, a logistic function between corn yield and mollic epipedon thickness and a linear function between corn yield and sediment deposition depth were fitted. Cross-validation implied that the two equations had acceptable accuracy. Therefore, prevention of soil erosion and reduction of adverse influences of overloaded sediment deposition are cornerstones of sustainable agriculture in the Chinese Mollisol region.

1. Introduction

Soil erosion is a great concern in the most of agricultural regions among the world due to its long-term negative effects on soil productivity (Montgomery, 2007; Zhou et al., 2015). Accelerated soil erosion may damage land resources, reduce soil quality, and result in decreased crop productivity, which may lead to a series of threats to agricultural sustainability (Wang et al., 2009; Ouyang et al., 2018). About 15.1% of global land was suffering from human-induced degradation, 83.6% of which was resulted by soil erosion and 40.4% of eroded land degradation occurred in Asia (Lal, 2001). Northeast China, one of four major Mollisol regions in the world, contributes approximately 18.9% to national food production and 33.1% to national total corn production (National Bureau of Statistics of China, 2012). Mollisol (USDA Taxonomy), which is named as black soil in China, is characterized by the presence of mollic epipedon with high organic matter content (Hu et al., 2017; Yan et al., 2017). However, the Mollisol's productivity and fertility have been declining during the past several decades due to severe soil erosion and large-scale cultivation. The statistical data (MWR et al., 2010) showed that the topsoil thickness of Mollisol (mollic epipedon thickness) mainly ranged from 50 to 80 cm in the 1950s, while it only ranged from 20 to 40 cm in the 2000. Serious soil erosion caused loss of 0.3–1.0 cm of the mollic epipedon per year in the Mollisol regions of the world (Li et al., 2006; Fenton, 2012). Especially, in some areas of the Chinese Mollisol region, the loessial parent material i.e., viscous parent material, with very little organic matter content has been exposed to the surface due to mollic epipedon loss, which caused a great loss of soil productivity (Zhang et al., 2007a; Xu et al., 2010). Liu and Yan (2009) reported that the loss of crop yield caused by soil erosion occupied 14.1% of total grain production in the

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Chinese Mollisol region. Therefore, the effects of mollic epipedon thickness reduction on soil productivity decline should be quantified in more details in order to provide scientific basis for policy-making.

Water erosion and tillage may affect soil redistribution, which influences topsoil thickness and further affects soil productivity (Christensen and McElyea, 1988; Larney et al., 2003). Up to date, three main methods were used to study the erosion influences on soil productivity, i.e., transects method, comparative plot method, and artificial topsoil removal method (also referred as desurfacing), among which the artificial topsoil removal method was widely accepted (Gao et al., 2015). The transect method involving crop yield comparison along transects was not widely used because it may have included the effects of other processes that are related to topography (Bakker et al., 2004). Bakker et al. (2004) indicated that the comparative plot method should be considered realistic after they studied crop yield reduction per 10 cm of topsoil loss using different methods. However, the comparative plot method is difficult to find similar characteristics and different historical erosion plots in a watershed (Gao et al., 2015). Many studies have investigated the relationship between topsoil thickness and soil productivity by artificial topsoil removal method. Oyedele and Aina (2006) used the soil classified as Ustoxic Dystropepts (USDA Taxonomy) to identify the responses of corn yield to erosion, and noted that corn yield decreased with a decrease in topsoil thickness, their results showed an average of 55% loss of crop yield occurred after removal of only 5 cm topsoil. The relationship between crop yield and topsoil removal was studied in cropland with Dark Brown Chernozemic sandy clay loams (Typic Haploborolls) by Larney et al. (2000), and the results showed that removal of 20 cm topsoil reduced crop yields by 53%. Izaurralde et al. (1998) conducted the experiment on Typic Cryoboroll and Typic Cryoboralf, and also revealed that decreasing in topsoil thickness markedly reduced crop yield. Wang et al. (2009) evaluated the effects of mollic epipedon thickness on crop yield in the Chinese Mollisol region, and demonstrated that the crop yield decreased exponentially with an increase in soil erosion, the average crop yield reductions per 10 cm of topsoil loss were 14.9% and 17.1%, respectively, for the fertilized and unfertilized treatments. However, the artificial topsoil removal method may exaggerate the negative effects of topsoil thickness on soil productivity due to the abrupt disappearance of topsoil in the initial several years (Bakker et al., 2004). Currently, there is limited information on quantifying the effects of topsoil thickness on crop yield in the Chinese Mollisol region, and above-mentioned methods and studies provided precious values in finding an effective approach to address how corn yield responses to mollic epipedon thickness in this region.

Sediments, as well as soil nutrients, are detached and transported from the soil surface at the upper slope position to the lower slope position or low-lying land along hillslope due to soil erosion (Walling, 1988). Consequently, the sediment deposition usually resulted in nutrients enrichment in the deposition area, which may lead to higher crop yield in the deposition area than that in the erosion area (Oyedele and Aina, 1998; Morgan, 2005; Soon and Malhi, 2005). Oyedele and Aina (1998) confirmed that 17% reductions in corn yield occurred in the severely eroded areas compared with those in the deposition areas. However, in the Chinese Mollisol region, a survey of corn yield in different areas of our study watershed in the 2013 indicated that, crop yield at the foot slope and the low-lying land was lower than that at the upper and middle slope. When extreme runoff with high sediment concentration occurred, overloaded sediments would deposit at the foot slope and bury crops, which could reduce the crop yield in the deposition area. Jiang et al. (2015) reported that a total of 2.59×10^9 kg of corn yields loss occurred due to flood disaster in the 2013 in 13 administrative regions of Heilongjiang Province, China, in which extreme rainfall occurred. Waterlogging imposes low oxygen stress on plants and leads to reduced plant growth and development, thus it remains a significant constraint to crop production, especially in areas with high rainfall and/or poor drainage (Bailey Serres and Voesenek, 2010; Zhang et al., 2016). Nevertheless, current researches regarding the effects of overloaded sediment deposition caused by extreme rainfall on crop yield are still lacking. Thus, it is important to evaluate the adverse impacts of overloaded sediment deposition on crop yield.

The objectives of this study were: (1) to ascertain the effects of mollic epipedon thickness on corn yield; (2) to evaluate the negative effects of overloaded sediment deposition on corn yield; (3) to establish and validate equations between corn yield and mollic epipedon thickness as well as sediment deposition depth in the Mollisol region of Northeast China. This study was conducted by two independent experiments: (1) to study the impacts of mollic epipedon thickness on corn yield, and the experimental method was to remove in-situ soil profiles from field to experimental plots in order to better simulate field situation and control conditions; (2) to investigate the negative effects of overloaded sediment deposition on corn yield at the corn seeding stage which is sensitive to corn growth, by artificial simulated sediment deposition.

2. Materials and methods

2.1. Study area

The Binzhouhe watershed with 375 km^2 area located at Bin County, Heilongjiang Province was selected in this study, and its geographical location is 127°25′60.0″–127°31′60.0“E and 45°43′0”–45°51′0″N (Fig. 1). This watershed has a temperate continental monsoon climate, which is warm and rainy during summer while cold and arid during winter. The mean annual temperature is 3.9 °C, and the frost-free period is approximately 148 d. The mean annual precipitation is 548.5 mm, of which 80% is concentrated from June to September. The black soil in this watershed is classified as Hapli–Udic Isohumosols in the Chinese Soil Taxonomy (CST), Mollisols (Agriboroll group) in the USDA Soil Taxonomy, or Haplic Phaeozems in the FAO-UNESCO system (NSSO, 1998; Chen et al., 2004; Gao et al., 2015). Its typical soil profile is A–B–C. The A horizon is the surface layer, which often refers to the topsoil or mollic epipedon, containing much more organic matter to give the soil a darker color than that of the lower horizons. The B horizon is commonly referred as subsoil, and it has a concentration of clay or minerals that are dark gray or brownish due to materials that

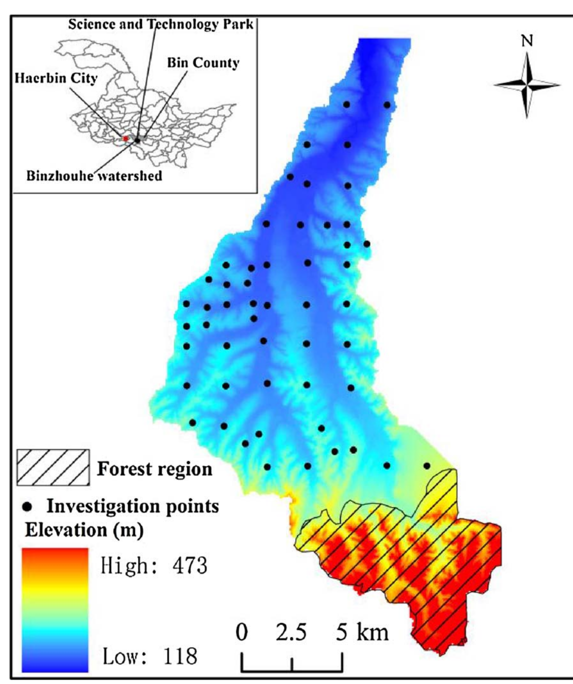

Fig. 1. Location of the Binzhouhe watershed and distribution of investigation points.

were leached from the A horizon. The C horizon is parent materials, including Quaternary lacustrine and fluvial sand beds or loess sediments (Sun and Liu, 2001; Gao et al., 2015). Corn (*Zea mays* L.) is one of the most widely planted crops with growing season from May to September and the irrigation is not applied in this region. Crop management practices and tillage method are similar within the whole watershed; especially the longitude ridge tillage is widely performed. The experimental area, used to simulate two independent experiments, was established in the Science and Technology Park of the Institute of Soil and Water Conservation, Heilongjiang Province. The soils in this experimental area had been under cultivation for about 80 years before the initiation of experiment. The plow layer depth is approximately 20 cm, which has a soil bulk density of 1.1 g cm^{-3}, 26.42 g kg^{-1} soil organic matter, and 1.43 g kg^{-1} total nitrogen.

2.2. Experimental set-up

2.2.1. Experimental plot layout

The experimental area covered an area of 160 m^2, which was 20 m long and 8 m wide, and was averagely divided into eight rectangular blocks. Seven experimental plots were established using a randomized complete block design (Gai, 2000) in each block with two independent experiments replicated four times, for a total of 48 experimental plots (Fig. 2). Each plot had an effective area (planting area) of 1.12 m^2 (1.4 m long and 0.8 m wide). To avoid the disturbance of crops in adjacent plots, there was a spacing of 0.3 m as an isolation zone between each plot.

2.2.2. Field investigation

An investigation in the study watershed was carried out before designing the experiments. The 2 km × 2 km grids were applied to determine investigation points where soil profiles were observed, meanwhile, additional investigation points were added when there was evident topography change. Thus, a total of 52 investigation points were selected (Fig. 1). In each point, mollic epipedon thickness, slope gradient and slope length were measured (Fig. 3), and the location of each point was recorded by GPS.

Fig. 3 showed that the landform in the watershed belongs to gentle slope with long slope length with a 1–8° slope gradient and a 200–1000 m slope length. The mollic epipedon thickness greatly varied from 0 to 80 cm, and it mainly ranged from 0 to 50 cm, but concentrated from 10 to 20 cm (Fig. 3). The mollic epipedon thickness at the lower reaches of watershed or lower slope position was greater than 50 cm. However, at the upper and middle slope position, the mollic epipedon thickness was less than 20 cm, and even nearly 0 cm at the severely eroded area.

2.2.3. Design of mollic epipedon thickness

According to the distribution of mollic epipedon thickness in the watershed, the mollic epipedon thicknesses with 0, 5, 10, 15, 20, 40, and 60 cm were chosen, and 60 cm treatment was designed as the control plot in this experiment (Fig. 2). Soil pans (140 cm long, 80 cm wide, and 75 cm deep) with 14 drainage holes (2 cm diameter) at the bottom were set at the experimental plots to study the impacts of mollic epipedon thickness on corn yield, whch was shown in Fig. 2 (the B, D, E and G blocks). Then, based on the design of mollic epipedon thickness, various in-situ Mollisol profiles with different mollic epipedon thicknesses from various investigation points were transported to the soil pans, which aimed to better simulate field situation and control conditions. To preserve the Mollisol structure, a set of wooden boxes (140 cm long by 80 cm wide) with variable depths (5, 10, 15 and 20 cm) were used to remove complete in-situ Mollisol profiles from cornfield to the soil pans. Detailed experimental procedures are as follows. (1) A 30 cm argillic layer with a soil bulk density of 1.30 g cm^{-3} was packed at the bottom of each soil pan at the experimental plots to simulate the C horizon. But this procedure was different in control treatment with 60 cm thick mollic epipedon, which was packed with a 10 cm argillic layer, largely because of the soil pan depth limitation. (2) For the treatments with 0, 5, 10, 15 and 20 cm thick mollic epipedon, a 20 cm argillic layer with a soil bulk density of 1.35 g cm^{-3} was packed on the top of the C horizon to simulate the B horizon. Then, 5, 10, 15 and 20 cm mollic epipedon were completely removed from the cornfield by using the corresponding deep wooden boxes and were placed on the top of the corresponding B horizons. Next, the wooden boxes were removed from the soil pans. (3) For the treatment with 40 cm thick mollic epipedon, a 40 cm mollic epipedon was removed from the cornfield by using two 20 cm deep wooden boxes and then these two obtained layers were placed above the C horizon in the same order occurred in the field. (4) For the treatment with 60 cm thick mollic epipedon, a 60 cm mollic epipedon was removed from the cornfield by using three 20 cm deep wooden boxes and then these three obtained layers were placed above the C horizon in the same order occurred in the field. Each packed soil

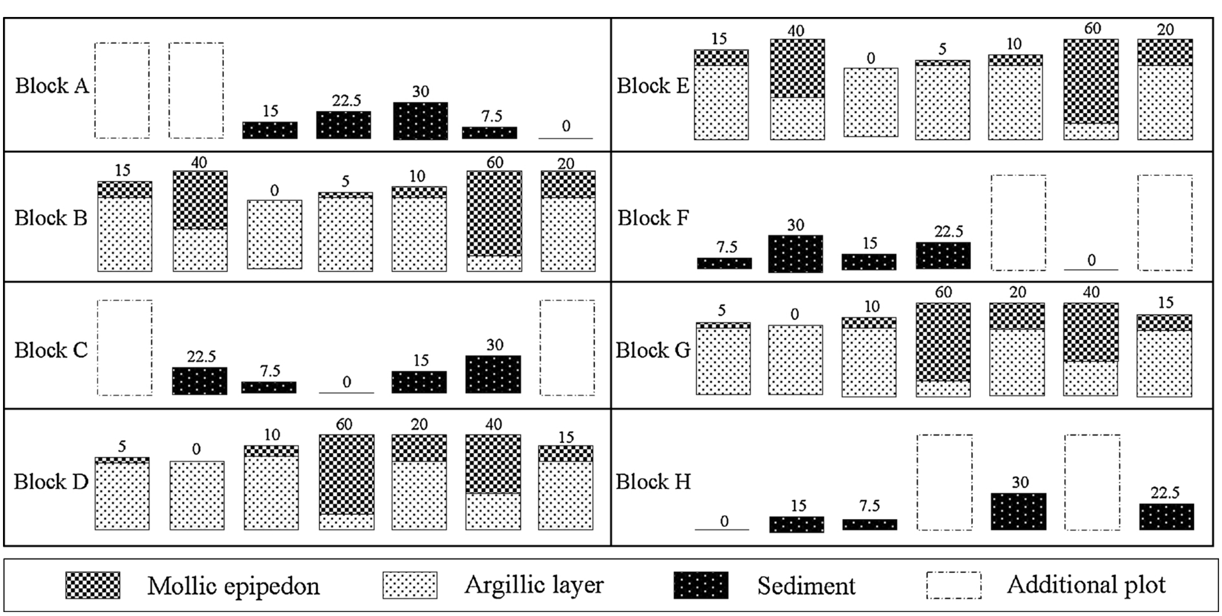

Fig. 2. Sketch map of experimental plot layout.

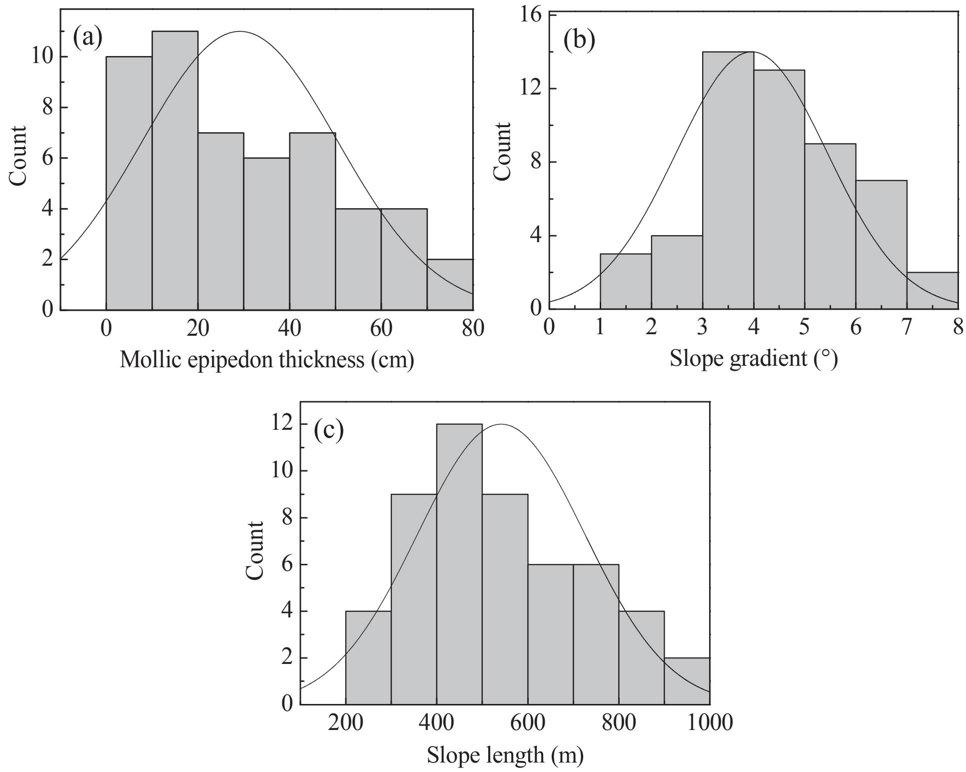

Fig. 3. Frequency distributions of mollic epipedon thickness (a), slope gradient (b) and slope length (c) in the Binzhouhe watershed.

layer was lightly raked for homogeneity before placing the next layer. The careful processes of removal, transport and place were applied in this experiment in order to reduce the artificial effects on the thickness and structure of in-situ Mollisol profile. A detailed description of the method used to move undisturbed in-situ soil profiles can be referred in Cássia De Brito Galvão et al. (2003).

2.2.4. Design of overloaded sediment deposition depth

The investigation of mollic epipedon thickness indicated that the mollic epipedon was nearly 80 cm thick in certain areas, such as the foot slope or low-lying land (Fig. 3). As mentioned above, the mollic epipedon thickness of study watershed mainly varied from 0 to 50 cm. The excessively thick mollic epipedon could be attributed to the overloaded sediment deposition, and the soil profiles observed at the foot slope showed that the original mollic epipedon was buried by 7.5–28 cm deposition layer. Therefore, the sediment deposition depths of 0–30 cm with 7.5 cm increments were simulated in this study. The treatment without sediment deposition (the sediment deposition depth was 0 cm) was considered as the control plot (Fig. 2).

This experiment was carried out on the original cultivated land, where the soil profiles were undisturbed with original 30 cm mollic epipedon thickness, which was shown in Fig. 2 (the A, C, F and H blocks). Earlier waterlogging caused more reduction in plant growth and yield than later waterlogging (Zhang et al., 2016). Thus, the corn seedling stage with 30 cm tall and 3–4 leaves was chosen in this experiment. Detailed experimental procedures were as follows. (1) Soil saturated moisture at the foot slope in the study watershed was measured initially, which was used to calculate the amount of soil and water that were needed to obtain the artificial simulated sediments. (2) 0–5 cm depth soils were collected from the foot slope in the study watershed. (3) Obtained soils and water were mixed with shovel based on the calculated soil saturated moisture. (4) Artificial simulated sediments were applied to bury the corn seedlings artificially, according to the different sediment deposition depths.

2.3. Corn sowing, management and yield measurement

The experiment was conducted from May to September in the 2014. The mean temperatures in May, June, July, August and September were 14.3, 22.9, 23.1, 21.9 and 15.5 °C, respectively, and the corresponding precipitation for each month were 91.4, 56.8, 115.5, 83.8 and 32.2 mm, respectively, based on the meteorological data of the Science and Technology Park of the Institute of Soil and Water Conservation. The mean temperature and precipitation in this year were close to the meteorological data obtained by other normal years in this location. On 10 May, the corn variety named China Agricultural University–2 was planted by farmers, with a spacing of 0.3 m inter-plant and 0.6 m intra-row. Because soybean (*Glycine max L. Merr.*) is another widely planted crop in the research region besides corn, it was selected to plant in the isolation zone, which could eliminate crop influences in adjacent plots. For each experimental plot, 27 corn seeds were sown on the 0.2-m-wide and 0.2-m-height longitude ridge, and only nine corn seeds were reserved for planting after the seedlings emerged. The first experiment was to study the mollic epipedon thickness impacts on corn yield, where corn seeds were sown on the soil pans. At the time of sowing, N and P fertilizer were applied to give an equivalent of 180 and 75 kg ha^{-1} in the form of urea and diammonium hydrogen phosphate, respectively. On 14 June, glyphosate isopropylamine salt was applied at a rate of 0.37 ml m^{-2} as an herbicide for weeds and N fertilizer was applied at a rate of 180 kg ha^{-1} as a top dressing. The experimental plots were not irrigated, so the corn growth completely depended on the natural rainfall. All above crop management practices followed local traditions. On 30 September, when the corns were at full maturity, all the corns of each plot were hand-harvested for yields: (1) all the corncobs were picked off and the numbers of corncobs were recorded; (2) the fresh weights of corns were measured; (3) the corn grains were manually stripped from the corncobs and air-dried; (4) the dry weights and the hundred-grain weights of corns were counted; (5) the corn yields of each plot were calculated according to the formula found by Liu et al. (2013a).

2.4. Data analysis

Statistical analysis was performed using SPSS 20.0 software (SPSS Inc., Chicago, IL, USA). Analysis of variance (ANOVA) and least significant difference (LSD) were conducted to examine the significant differences among different treatments with two independent experiments at the 95% confidence level. The regression analysis was applied to fit the equations between corn yield and mollic epipedon thickness as well as sediment deposition depth.

To ensure the independence of the data used to establish and validate the equations, 75% of the total data were randomly selected to establish the equations and 25% of the total data were used to validate the equations. In total, we repeated the random selection and evaluation 20 times, and gave mean values for all indicators, both in fitting and in validating, by using SPSS 20.0 software. The determination coefficient (R^2), the Nash-Sutcliffe simulation efficiency (E_{NS}) (Nash and Sutcliffe, 1970), the root mean square error (RMSE) (Wu et al., 2018), the mean relative error (MRE) and the mean error (ME) were used to evaluate the prediction accuracy of the equations developed in this study. The mathematical expressions for R^2, E_{NS}, RMSE, MRE, and ME are:

$$R^2 = \frac{\left[\sum_{i=1}^{n} (O_i - \bar{O})(P_i - \bar{P})\right]^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2 \sum_{i=1}^{n} (P_i - \bar{P})^2} \quad (1)$$

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2} \quad (2)$$

$$\text{RMSE}=\sqrt{\frac{\sum_{i=1}^{n} (O_i\text{-}P_i)^2}{n}} \quad (3)$$

$$\text{MRE}=\frac{\sum_{i=1}^{n} \frac{P_i\text{-}O_i}{O_i}}{n} \quad (4)$$

$$\text{ME}=\frac{\sum_{i=1}^{n} P_i\text{-}O_i}{n} \quad (5)$$

Where O_i is the observed value, P_i is the predicted value, $\bar{O}$ is the mean of the observed value, $\bar{P}$ is the mean of the predicted value, and n is the number of data.

The R^2 value indicates the strength of the relationship between observed and predicted corn yields. The E_{NS} value indicates how well observed versus predicted corn yields fit the 1:1 line. The value ranges of R^2 and E_{NS} are 0–1 and $-\infty$–1, respectively (Nash and Sutcliffe, 1970). If R^2 and E_{NS} are close to 1, the equation prediction is considered 'perfect'; while if R^2 and E_{NS} are close to 0, the equation prediction is considered 'poor'. Typically, when $R^2 > 0.6$ and $E_{NS} > 0.5$, the equation prediction is acceptable or satisfactory (Santhi et al., 2001). Additionally, negative and positive values of ME indicate under-prediction and over-prediction of equations, respectively (Bonfatti et al., 2018).

3. Results and discussion

3.1. Mollic epipedon thickness impacts on corn yield

The corn yield decreased with decreasing mollic epipedon thickness (Fig. 4). For the control treatment with 60 cm thick mollic epipedon, the corn yield was 7934 kg ha^{-1}. For the treatments with 40 and 20 cm thick mollic epipedon, the corn yields were 7910 and 7669 kg ha^{-1}, respectively, corresponding to the corn yield reductions of only 0.3% and 3.3%, respectively, compared with that of the control treatment. There was no significant difference in the corn yield among the treatments with 60, 40 and 20 cm thick mollic epipedon (Table 1). For the treatments with 15, 10, 5 and 0 cm thick mollic epipedon, the corn yields were 7285, 6681, 6248 and 6017 kg ha^{-1}, respectively, and the corresponding corn yield reductions were 8.2%, 15.8%, 21.3% and 24.2%, respectively, compared with that of the control treatment. There were significant differences in the corn yield among the treatments with 15, 10 and 5 cm thick mollic epipedon, but there was no significant difference in the corn yield among the treatments with 20 and 15 cm, 5 and 0 cm thick mollic epipedon (Table 1). Compared with the treatments where the mollic epipedon thickness was more than 20 cm, the corn yield was more strongly affected by mollic epipedon thickness when the mollic epipedon thickness was less than 20 cm (Fig. 4). We could infer that 20 cm was the minimum mollic epipedon thickness for maintaining corn yield, and the corn yield may dramatically decrease if the mollic epipedon thickness was less than 20 cm. Thus, the mollic epipedon plays a dominant role in maintaining corn yield.

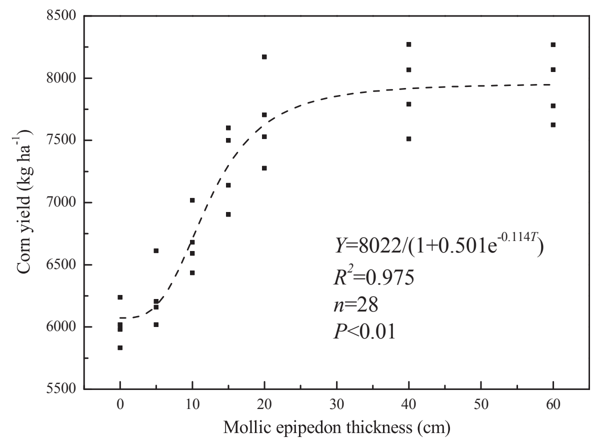

Fig. 4. Relationship between corn yield and mollic epipedon thickness.

Table 1
Descriptive statistics of corn yields at different mollic epipedon thicknesses.

Mollic epipedon thickness (cm)	Corn yield (kg ha^{-1})				
	Max.	Min.	Mean	SD	SE
60	8269	7623	7934 a	290	145
40	8270	7512	7910 a	330	165
20	8169	7276	7669 ab	377	188
15	7599	6903	7285 b	322	161
10	7018	6434	6681 c	247	123
5	6611	6018	6248 d	255	127
0	6238	5832	6017 d	168	84

Values at the column followed by different letters are significantly different for one variable within the same column at the 0.05 probability level. SD is standard deviations; SE is standard errors. The same as follows.

The artificial topsoil removal method is widely used to simulate topsoil thickness impacts on crop production. Some studies have applied this method to quantify the effects of mollic epipedon thickness on corn yield in the Chinese Mollisol region. Zhang et al. (2007b) proposed that the corn yield reductions were 1.9%, 4.7%, 34.6% and 95.7% when mollic epipedon thicknesses were 25, 20, 10 and 0 cm, respectively. Sui et al. (2009) concluded that the loss of mollic epipedon thicknesses of 5, 10, 20 and 30 cm reduced corn yields by 10%, 13%, 46% and 73% reductions, respectively. Obviously, the corn yield reductions with decreased mollic epipedon thicknesses in our study were markedly lower than those of previous studies. Bakker et al. (2004) summarized that the average crop yield reduction was 4.3% for studies using the comparative plot method, whereas the average crop yield reduction was 10.9% for investigations based on the transect method and 26.6% for experiments by the artificial topsoil removal method when 10 cm of topsoil loss was simulated. They also showed that the crop yield reduction of

4.3% per 10 cm of topsoil loss based on the comparative plot method should be considered realistic because of the overestimated effects of soil erosion on productivity by other two methods (Bakker et al., 2004). In this study, an average crop yield reduction of 4.0% per 10 cm of mollic epipedon thickness deceased was close to the realistic estimate of 4.3%, which indicated that our experimental method, removing in-situ soil profiles from field to experimental plots, employed similar functions to the comparative plot method, and overcame the limits of artificial topsoil removal method.

No matter what method used, most researches have shown that crop yield reduced associated with the decrease of topsoil thickness. This is primarily because decreased topsoil thickness caused by soil erosion leads to specific mismatches between crop demand and soil supply, like a water deficit, nutrient deficit, and insufficient rooting possibilities (Bakker et al., 2004). Water erosion affects the transport of soil materials along with soil nutrients under the impacts of raindrop detachment and runoff scouring (Ouyang et al., 2018). Plant root growth is hindered by clayey subsoil or bedrock, which adversely affects crop yield (Kosmas et al., 2001). In the absence of sufficient fertilizer applications, a shortage of nutrients will cause a rapid decline in crop yield. Oyedele and Aina (2006) confirmed that the soil organic matter content significantly decreased with a decreased topsoil thickness, and Bathelder and Jones (1972) concluded that the nutrient deficiency was principally responsible for reduced crop yield. Therefore, protecting topsoil from soil erosion is essential for maintaining crop production.

3.2. Overloaded sediment deposition impacts on corn yield at the corn seedling stage

The corn yield decreased with increasing sediment deposition depth at the corn seedling stage (Fig. 5). For the control treatment without sediment deposition (the sediment deposition depth was 0 cm) at the corn seeding stage, the corn yield was 7955 kg ha^{-1}. When the sediment deposition depth at the corn seeding stage ranged from 7.5, 15, 22.5 to 30 cm, the corn yields were 7637, 7076, 6241 and 5431 kg ha^{-1}, respectively, and the corresponding corn yield reductions were 4.0%, 11.0%, 21.5% and 31.7%, respectively, compared with that of the control treatment. There were significant differences in the corn yield among these five treatments (Table 2). In addition, the average reduction in corn yield was 84.1 kg ha^{-1} per one centimeter of sediment deposition depth increase, indicating that overloaded sediment deposition had significant negative effects on corn yield at the corn seedling stage.

The adverse effects of overloaded sediment deposition on crop yield at the corn seedling stage can be explained as follows. Firstly, the corn growth is inhibited by mechanical damage when the corn seedlings are

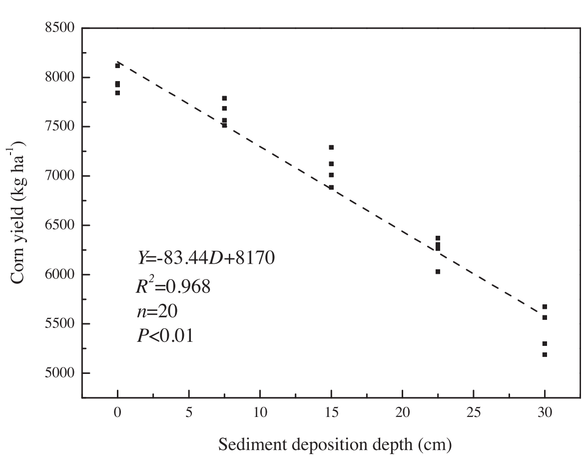

Fig. 5. Relationship between corn yield and sediment deposition depth at the corn seedling stage.

Table 2
Descriptive statistics of corn yields at different sediment deposition depths at the corn seeding stage.

Sediment deposition depth (cm)	Corn yield (kg ha^{-1})				
	Max.	Min.	Mean	SD	SE
0	8119	7841	7955 a	117	59
7.5	7788	7511	7637 b	124	62
15	7290	6884	7076 c	173	86
22.5	6369	6027	6241 d	149	75
30	5672	5188	5431 e	225	113

buried by sediments. Secondly, overloaded sediment deposition impedes the photosynthesis of corn seedlings which is essential for dry matter accumulation and crop yield formation (Wang et al., 2007). Thirdly, overloaded sediment deposition generally occurs after extreme rainfall events which can cause waterlogging. Waterlogging stress adversely affects plant growth and development, as well as nutrient uptake and thus results in reduction of crop yield (Zhang et al., 2016). Yu et al. (2015) proposed that under waterlogging conditions, the soil became deficient in oxygen because the gas exchange rate with the atmosphere at the soil surface was reduced. Capon et al. (2009) also confirmed that waterlogging caused a shortage in oxygen availability to plants, which affected the root system directly and the shoot system indirectly. Zhang et al. (2015) demonstrated that waterlogging affected expression of genes coding for ethylene biosynthesis, nitrogen metabolism and cell wall degeneration. Finally, insufficient photosynthesis and waterlogging may influence the root respiration. The insufficient photosynthesis leads to a deficiency in substrate supply, thereby affects root respiration (Craine et al., 1999). Waterlogging can induce the death of root cells and decrease cell permeability under long-lasting conditions of poor aeration (Xu and Qi, 2001), then influences root respiration. Recently, Chen et al. (2017) examined the extreme rainfall effects on soil respiration and ascertained that the extreme rainfall had profound impacts on soil respiration and its components, that is, autotrophic and heterotrophic respiration. They proposed that compared with those in other years, autotrophic and heterotrophic respiration were reduced by 36.8% and 59.1%, respectively, in the record wet year. Collectively, combined impacts of mechanical damage, plant photosynthesis, waterlogging, and soil respiration eventually resulted in the reduction of corn yield. Further exploration is needed to identify the contribution of each factor to corn growth and production. These inferences are helpful in understanding why deposition area has instead lower crop yield than erosion area in the extreme rainfall year. The soil nutrient enrichment caused by better chemical properties and higher soil thickness is normally beneficial to crop growth. However, this study provided a new insight into the uncommon perception that overloaded sediment deposition had more significant negative impacts than the benefit of nutrient enrichment on corn yield in the extreme rainfall year.

By using magnetic susceptibility measurements to quantify the soil redistribution in the Northeast region of China, Liu et al. (2015) proposed that the maximum sediment deposition (25.1%) was observed at the foot slope. Zhang et al. (2006) also noted that many eroded soil materials associated with runoff were re-deposited in the low-lying land. These statements suggest that overloaded sediment deposition is more likely to take place at the foot slope and in the low-lying land than other areas in the watershed. Hence, it is necessary to quantify how overloaded sediment deposition influences crop growth and production in the deposition area. This experiment, a preliminary study to evaluate the effects of overloaded sediment deposition on corn yield, is mainly focused on the corn seedling stage which is sensitive to corn growth (Liu et al., 2013b), and further studies are needed throughout the corn growth period.

3.3. Equation fittings and validations

3.3.1. Equation fitting and validation between corn yield and mollic epipedon thickness

The result of curve simulation showed that the variation of corn yield with decreasing mollic epipedon thickness was a typical S-curve, which is the described equation of a smooth S-curve with a fixed turning point (Darmani et al., 2003). To ensure the independence of corn yield data used to fit and validate the equation, 18 data were randomly selected from the 24 data to establish a logistic equation (one of the S-curves), and the remaining six data were used to validate the equation except the date observed from the treatment with 0 cm mollic epipedon. The equation between corn yield and mollic epipedon thickness was fitted as follow:

$$Y=\frac{8022}{1+0.501e^{-0.114T}} \quad (R^2 = 0.975,\ n = 18,\ P < 0.01) \tag{6}$$

where Y is corn yield (kg ha^{-1}), and T is mollic epipedon thickness (cm).

Values predicted by Eq. (6) were cross validated by observed data which were not used in the fitting the equation. Predicted and observed values by Eq. (6) were distributed along the 1:1 line, implying that the predicted values were close to the observed values (Fig. 6a). For Eq. (6), the RMSE value was 303.7 and the MRE value was only 4.1%. The 0.974 for R^2 value was greater than 0.6, indicating that the correlation between the predicted and observed corn yields was acceptable (Nash and Sutcliffe, 1970). The 0.800 for E_{NS} value was greater than 0.5, indicating a satisfactory agreement for equation validation (Santhi et al., 2001), and the ME value was positive, suggesting an overestimation (Table 3). Therefore, Eq. (6) is suitable for the corn yield predictions in different mollic epipedon thicknesses in the Mollisol region of Northeast China.

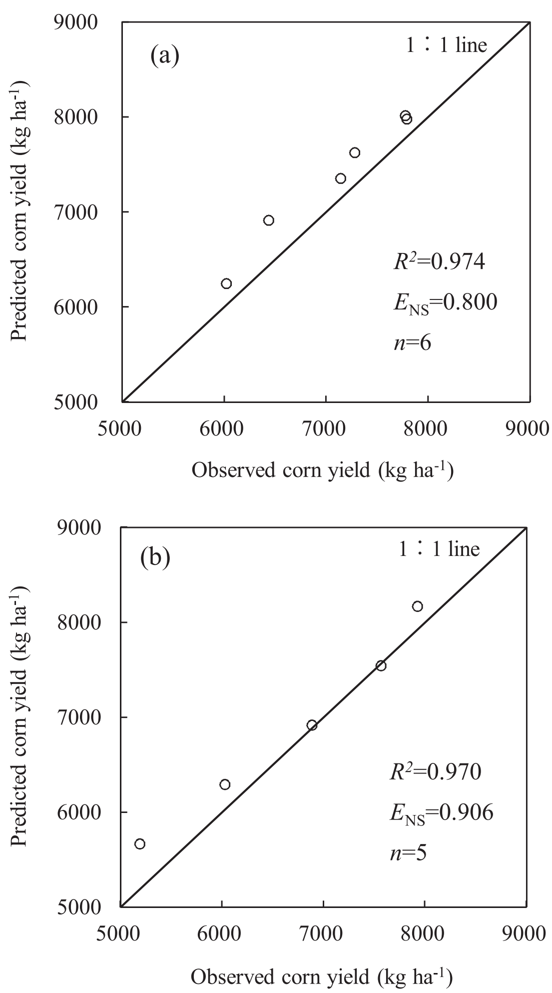

Fig. 6. Comparisons of observed and predicated values of corn yields for mollic epipedon thickness (a) and sediment deposition depth (b).

Table 3
Validation results for both equations.

Equation	n	R^2	E_{NS}	RMSE	MRE (%)	ME
$Y = 8022/(1 + 0.501e^{-0.114T})$	6	0.974	0.800	303.7	4.1	286.4
$Y = -83.44D + 8170$	5	0.970	0.906	269.4	3.5	201.4

Values are the means of statistical parameters repeated 20 times. Y is corn yield (kg ha^{-1}); T is mollic epipedon thickness (cm); D is sediment deposition depth (cm); n is the number of equation validation data; R^2 is determination coefficient; E_{NS} is Nash-Sutcliffe simulation efficiency; RMSE is root mean square error; MRE is mean relative error; ME is mean error.

3.3.2. Equation fitting and validation between corn yield and sediment deposition depth at the corn seedling stage

The result of curve simulation showed that the corn yield decreased linearly with increasing sediment deposition depth at the corn seedling stage. To ensure the independence of corn yield data used to fit and validate the equation, 15 data were randomly selected from 20 data to establish the linear equation, and the remaining five data were used to validate the equation. The equation between corn yield and sediment deposition depth was fitted as follow:

$$Y=-83.44D+8170 \quad (R^2 = 0.968,\ n = 15,\ P < 0.01) \tag{7}$$

where Y is corn yield (kg ha^{-1}), and D is sediment deposition depth (cm).

Values predicted by Eq. (7) were cross validated by observed data which were not used in the fitting the equation. Predicted and observed values by Eq. (7) were distributed along the 1:1 line, implying that the predicted values were close to the observed values (Fig. 6b). For Eq. (7), the RMSE value was 269.4 and the MRE value was only 3.5%. The 0.970 for R^2 value was greater than 0.6, indicating that the correlation between the predicted and observed corn yields was acceptable (Nash and Sutcliffe, 1970). The 0.906 for E_{NS} value was greater than 0.5, indicating a satisfactory agreement for equation validation (Santhi et al., 2001), and the ME value was positive, suggesting an overestimation (Table 3). Thus, Eq. (7) is suitable for the corn yield predictions in different sediment deposition depths in the Chinese Mollisol region.

4. Conclusions

To evaluate the relationships between corn yield and both mollic epipedon thickness and sediment deposition depth, simulated field experiments based on seven mollic epipedon thicknesses (0, 5, 10, 15, 20, 40 and 60 cm) and five sediment deposition depths (0, 7.5, 15, 22.5 and 30 cm) at the corn seedling stage were conducted in two independent experiments, respectively, in the cultivated Mollisol of Northeast China. Especially, a method of removing in-situ soil profiles from field to experimental plots was applied to study mollic epipedon thickness impacts on corn yield. The results showed that the corn yield decreased as mollic epipedon thickness decreased. The decreased mollic epipedon thickness significantly reduced corn yield in the treatments with less than 20 cm of mollic epipedon thickness. Compared with the control treatment with 60 cm mollic epipedon, the corn yield reductions were 8.2%, 15.8%, 21.3% and 24.2%, respectively, for the treatments with 15, 10, 5 and 0 cm mollic epipedon. The results also displayed that the adverse impacts of overloaded sediment deposition on corn yield, and the increasing sediment deposition depth markedly reduced corn yield at the corn seedling stage. Once corn seedlings were totally buried by sediments (the sediment deposition depth was 30 cm), the corn yield reduction reached up to 31.7%, compared with the control treatment without sediment deposition. Furthermore, the equations between corn yield and both mollic epipedon thickness and sediment deposition depth were fitted and the cross-validation results indicated that the two equations have satisfactory prediction accuracy. In conclusion, our results highlight the significant effects of mollic epipedon thickness and overloaded sediment deposition on corn yield. It is thus imperative to control soil erosion by implementing conservation tillage measures to maintain soil productivity in the Mollisol region of Northeast China.

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