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Article

Influence of different tillage depth on soil and maize yields in three growing seasons in the North China Plain

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Abstract: Rotary tillage is a main management tillage practices and widely applied in the North China Plain. However, the long term rotary tillage (depth of 20 cm) results in soil compaction and plow pan formation, which reduces water use efficiency and nutrient uptake, and then impedes the yield increase. In this study, a 3-year field experiment was conducted to investigate the influence of different depths of tillage on soil bulk density, field capacity, water use, photosynthetic rate, nutrients and maize yields in the North China Plain. Three depths of tillage (D20, depth of 20 cm; D25, depth of 25 cm; D30, depth of 30 cm) were assessed. D25 and D30 significantly reduced soil bulk density and improved field capacity in 10-20 and 20-30 cm soil layer, compared to D20. Soil water consumption for D25 was significantly higher 10.12% and 6.61% than that for D20 and D30, respectively. Photosynthetic rate for D25 significantly improved than that for D20 and D30. Total nitrogen in 0-20cm soil layer decreased with the depths of tillage. The maize yields for D25 significantly increased by 20.92% and 21.56% compared to that for D20 and D30, respectively. Structural equation models showed that the total effects of tillage, total nitrogen, photosynthesis and soil water consumption on yields were 0.019, -0.628, 0.121, and 0.895 (path coefficients λ), respectively. The results demonstrated that D25 could improve maize yields, water use efficiency, photosynthetic rate by improving soil water consumption. Depth of 25 cm is optimal tillage practice for the maize production in the North China Plain.

Keywords: Soil bulk density; Water consumption; Rotary tillage; Photosynthetic rate; Field capacity

1. Introduction

The planting of summer maize plays an important role in the North China Plain due to the suitable temperature and light resources [1]. However, long-term traditional farming and fertilization resulted in soil compaction, degradation and water shortage, which threaten the agricultural production of maize [2]. Extremely, the soil compaction can depress crop yields, and the soil with high bulk density can impede root growth, which limits water and nutrient absorption of crops. Tillage has been one of the most vital agricultural management practices for improving the maize yield [3, 4]. There are many benefits of tillage, such as preparing suitable soil environment for seeds and seedlings, inhibiting diseases of weeds, insects and plant in soil [5](Zhang, Z. et al., 2021). Tillage practices in agriculture include plowing tillage, rotary tillage and subsoiling, and tillage depths can affect the crop yields [6-8]. Conventional tillage and deep tillage practices can both alter bulk density, plow pan (the compacted layer of soil), aggregate stability, total porosity, and decrease surface runoff and erosion. They affect soil physical and chemical parameters resulting in the changes of soil water transmission properties, soil water storage and crop yields [9, 10].

Conventional tillage methods on the North China Plain generally include maize straw is crushed and returned to the field, rotary tillage, and the typical tillage depth after

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harvest is nearly 20 cm. Rotary tillage is convenient and reduces cost compared to the plowing tillage and subsoiling [11]. However, the working depth is shallow, and the long-term rotary tillage results in a shallow plowing layer and thick plow pan in the soil [12]. Deep tillage tills deeper than 25 cm, and the main function of deep tillage is to alleviate subsoil compaction. The benefits of deep tillage may break up of the 20-40 cm soil layer in the plow pan, which improved soil structure, facilitated root growth, and increased water infiltration and movement [13, 14]. The deep tillage with straw retention treatment increased the crop yields in comparison to the shallow tillage treatment [8]. Schneider et al. [11] found that deep tillage increased the crop yields by 6% on average. The depth of subsoiling is ranged of 25-35 cm, which can break the plow pan without inverting the infertile subsoil, eliminate the soil compaction, and improve soil moisture and root growth, thereby increasing the crop yields than the conventional tillage [15-18]. Subsoiling improved soil infiltration capacity, maintained the soil moisture within the least limiting water range for a longer time, and then increased the crop yields than the rotary tillage [19]. Compared with rotary tillage, the net photosynthetic rate, plant water status, root length density, and soil moisture increased under subsoiling tillage, which resulted in the increase of maize yields [16].

Bulk density of soil will change with different climates, topography, parent materials and different agricultural practices [20]. Soils with a high bulk density decreased the microbial activities including fungi and aerobic bacteria [21], which affected the crop yield. Tillage operations loosened the soil in 0-20cm soil layer and reduced the bulk density of the tilled layer, which was contribute to root for extending and penetrating to 0-20 cm soil depth [22]. Deep tillage had an important influence on soil bulk density and infiltration rate compared to shallow tillage systems, and increased crop yield [23].The increase of soil bulk density in the top 10-20 cm soil layer reduced air-filled pore space [10], which caused the reduction of soil water moisture in the top soil. Lamptey et al. [24] reported that an improvement in soil water moisture improved photosynthetic activity resulted in increasing crop yield. The net photosynthetic rate of maize leaves increased by 40% under subsoiling compared to rotary tillage [16]. Tillage promotes root and nutrients (N, P, K) from the top soil layer downward to the lower soil layer. The root growth was improved, and the accumulation of N, P, and K in subsoiling significantly increased, resulting in an increase by 12.8% in grain yields compared to conventional soil management [25].

In the the North China Plain, shallow rotary tillage with the maize straw is the major tillage management. However, the common tillage depth of rotary tillage is 0-20cm. This single annual rotary tillage practice forms a hard plow pan in the 20-30 soil layers, which adversely affected crop yields. The impacting mechanism of the plow pan depth on maize yields is unknown and needs to be investigated. In this study, a 3-year field trial in Xintai city was conducted, in which the same fertilization regime and different plow pan depth were applied to an annual maize. The main objectives of this study were to (1) assess the influence of plow pan depth on soil bulk density and field capacity; (2) investigate whether plow pan depth affects the photosynthetic rate and the nutrient in soil; (3) clarify the impacting mechanism of plow pan depth on the maize yields..

2. Materials and Methods

2.1 Experimental site description

The study was performed at Ningjing experimental sites, Xintai District, Hebei Province of China in the 2017-2019 growing seasons of maize. This site was located at 114°53' E, 37°37' N, and elevated at 25-35 m a.s.l. Its environmental conditions represent annual mean precipitation of 501 mm (mainly in June and August), annual mean temperature of 13.0 °C.

The soils in this study was light loam in 0-21 cm soil layer, heavy loam in 21-45 cm soil layer, light clay in 45-90 cm soil layer, and sandy loam in 90-100 cm soil layer. The daily air temperature and precipitation data during 2017-2019 was shown in Figure 1.

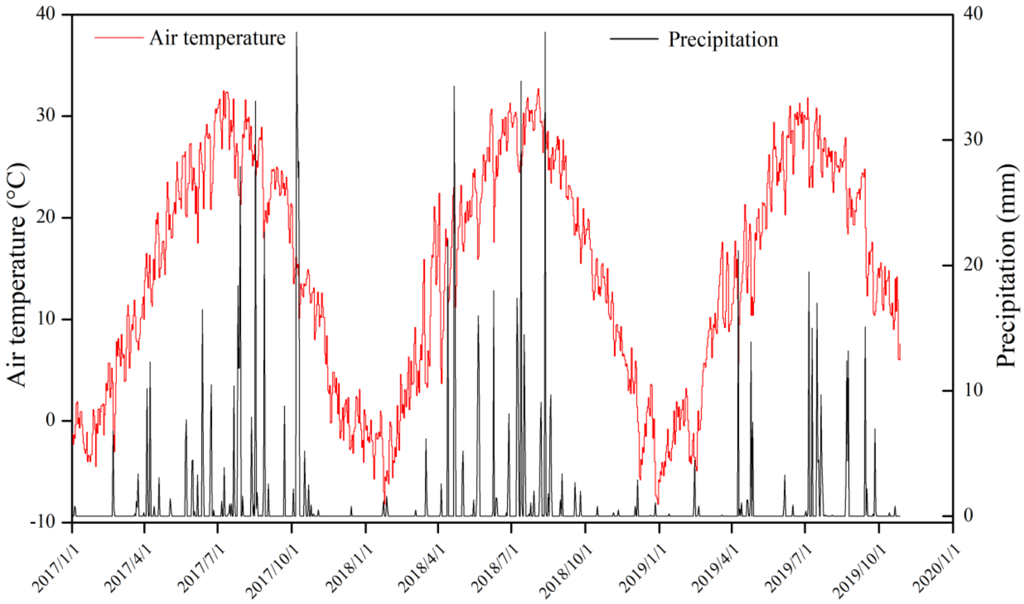

Figure 1. Daily air temperature and precipitation data in 2017-2019 at experimental site

2.2 Experimental design and field management

Three tillage practices were used as experimental treatments: tillage depth of 20, 25 and 30 cm, and plough pan thickness was 10, 5 and 0 cm, respectively. All treatments were conducted in triplicate for a total of 9 plots, and plot areas were 90 m2 (9.0 m×10.0 m). Fertilizer included slow-release fertilizer, water-retaining agent and calcium ammonium sulfate as shown in Table 1. Maize cultivar 'Weike 966' was used in this study, and the seeds were sown in mid-June every year and harvested in late-September.

Table 1 Experimental design of maize farmland

Treatments	**Tillage depth /(cm)**	**Plow pan thick-ness /(cm)**	**Fertilizer（kg·hm^{-2}）**
			Slow-release fertilizer + water-retaining agent + calcium ammonium sulfate
D20	20	10	150+60+150
D25	25	5	150+60+150
D30	30	0	150+60+150

2.3 Sampling and measurement

In 0 to 60 cm soil layer, soil samples were collected by using a soil drill at the maize growth stages of Pre-sowing, Jointing, Bell and Silking. Total nitrogen (N), total phosphorus (P) and total potassium (K) were determined by J200 laser spectral element analyzer. Soil bulk density and soil water content were determined using the oven-drying method [26]. Soil storage water consumption was calculated using equation as follows:

$$\Delta W = 10\sum_i^n \gamma_i H_i(\theta_{i1} - \theta_{i2}) \quad (1)$$

Water consumption was calculated using equation as follows:

$$ET_{1-2} = \Delta W + M + P \quad (2)$$

Where ΔW is soil storage water consumption in specific growing stage; ET_{1-2} is water consumption in specific growing stage; i is the numeration of soil layer; n is the total number of soil layer; γ_i is dry bulk density in i soil layer (g·cm^{-3}); H_i is the soil depth in i soil layer (cm); θ_{i1} and θ_{i2} are the initial and final water content in i soil layer in specific growing stage, respectively; M is the irrigation amount in specific growing stage; P is the effective precipitation.

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The photosynthetic rate was determined by Portable photosynthetic determination system. The yield of maize after harvest was determined by all the productive corn in each plot.

2.4 Statistical analysis

Figures were plotted using Origin 8.1 (Graphing and data analysis software, Northampton, Massachusetts, USA). Statistical analyses were performed using SPSS 22.0. Analysis of variance (ANOVA) was conducted by least significant difference (LSD) method at the $p < 0.05$ level. Nonmetric multidimensional scaling (NMDS) was conducted using Canoco 5.0. Structural equation models (SEM) was performed using SPSS Amos 22.0.

3. Results

3.1 Soil bulk density and field capacity

Numbered lists can be added as follows:At 0 - 10 cm soil depth, soil bulk density was significantly lower for D25 than D20 and D30 in 2017, 2018, while there was no significant difference between D20 and D30 (Figure 2). In 2019, soil bulk density wan significantly higher for D20 than D25 and D30. At 10 - 20 and 20 - 30 cm soil depth, soil bulk density was significantly different among D20, D25 and D30, and gradually decreased with the increase of the topsoil depth in 2017, 2018 and 2019. However, no significant difference occurred among D20, D25 and D30 at 40 - 60 cm soil depth. With the increase of the soil depth, soil bulk density increased except for 20 -30 soil depth (Figure 2). At 0 - 10 cm soil depth, the soil bulk density was about 0.9 $g \cdot cm^{-3}$, while 0.7 - 1.2 $g \cdot cm^{-3}$ at 10 - 20 cm soil depth, 1.4 - 1.7 $g \cdot cm^{-3}$ at 20 - 30 cm soil depth, and about 1.5 $g \cdot cm^{-3}$ at 10 - 20 cm soil depth. The soil bulk density was highest at 20 -30 soil depth, which was because this soil layer was the plow pan. Breaking the plow pan decreased the soil bulk density at 20 - 30 cm soil depth.

The field capacity was significantly lower for D20 than D25 and D30 at 0 - 10 cm soil depth in 2017; while it was significantly higher for D30 than D20 and D25 in 2018; and it decreased with the increase of the topsoil depth in 2019 (Figure 3). At 10 - 20 cm soil depth, the field capacity increased with the increase of the topsoil depth in 2017 and 2019; while it was significantly higher for D30 than D20 and D25 in 2018; and it was highest for D30 among the three treatments in the three years. At 20 - 30 cm soil depth, the trend of the field capacity was similar to that at 10 - 20 cm soil depth. At 40 - 60 cm soil depth, the field capacity was mainly no significant difference for the three treatments in the three years. With the increase of the soil depth, field capacity mainly decreased (Figure 3). At 0 - 10 cm soil depth, the field capacity was above 0.38, while 0.25 - 0.45 at 10 - 20 cm soil depth, 0.18 - 0.40 at 20 - 30 cm soil depth, and about 0.22 at 10 - 20 cm soil depth. For D20 and D25, the field capacity was lowest at 20 - 30 cm soil depth among the four soil layers; while for D30, it increased than D20 and D25. Breaking the plow pan increased the field capacity at 20 - 30 cm soil depth.

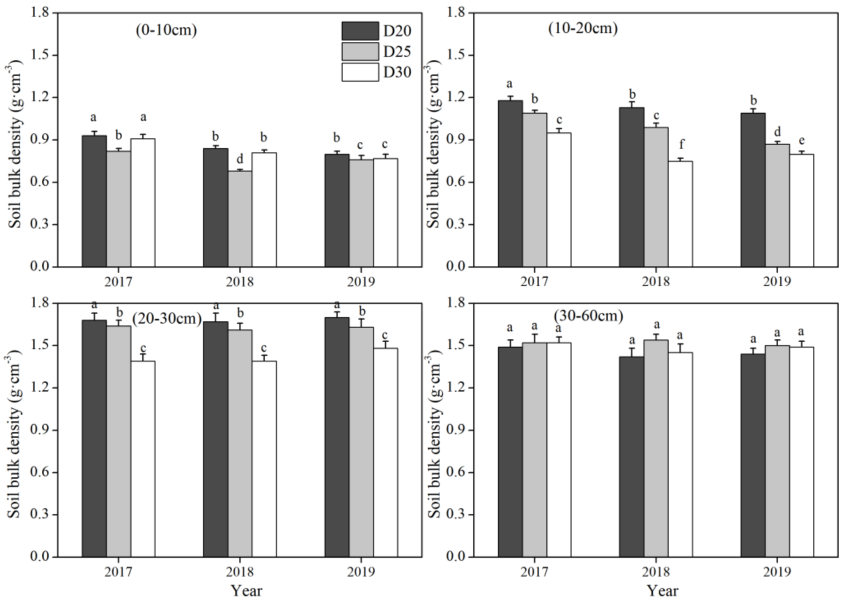

Figure 2. The soil bulk density for 20 cm topsoil depth (D20), 25 cm topsoil depth (D25), and 30 cm topsoil depth (D30) at 0 - 60 cm soil depth in 2017, 2018 and 2019.

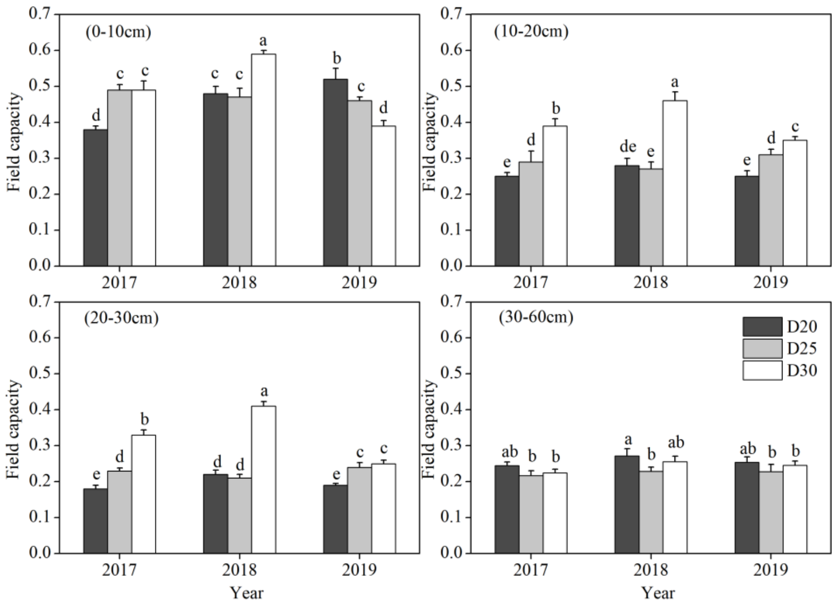

Figure 3. The field capacity for 20 cm topsoil depth (D20), 25 cm topsoil depth (D25), and 30 cm topsoil depth (D30) at 0 - 60 cm soil depth in 2017, 2018 and 2019.

3.2. Photosynthetic rate and yield

At the jointing stage, the photosynthetic rate was lowest for D30 in 2017, but it was highest in 2018 and 2019 (Figure 4). For D25 it was in the middle in the three treatments. At the bell stage, it was highest for D25 in the three years, and lowest for D30. At silking stage, it was the similar trend with the bell stage. In the three growth stages, it was lowest for the silking stage, and for the other growth stages it was no obvious difference.

Yield of maize was significantly higher for D25 than that for D20 and D30, and no significant difference for D20 with D30 in the three years (Figure 5). Yield of maize for the same treatment was no significant difference in the three years. Yield of D25 was higher 20.92% and 21.56% than that of D20 and D30, respectively.

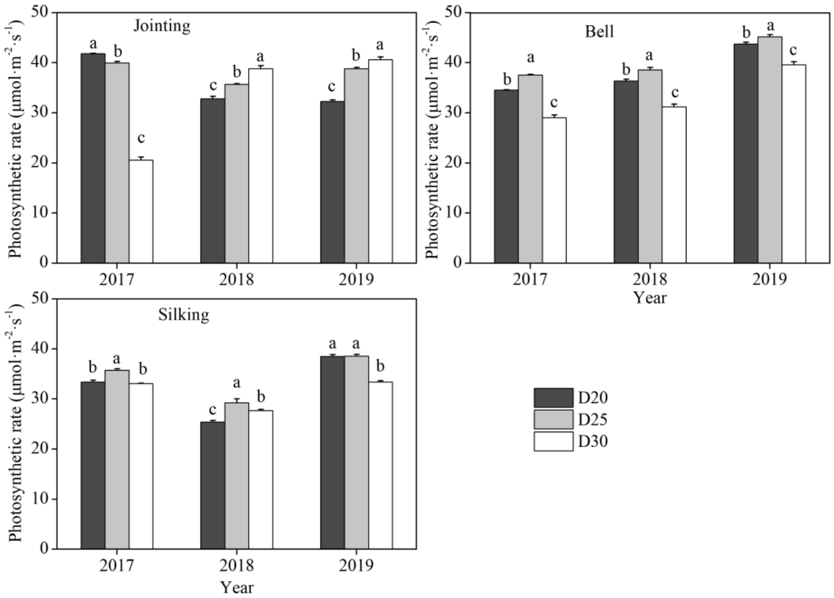

Figure 4. Photosynthetic rate for 20 cm topsoil depth (D20), 25 cm topsoil depth (D25), and 30 cm topsoil depth (D30) at jointing, bell and silking periods of maize in 2017, 2018 and 2019.

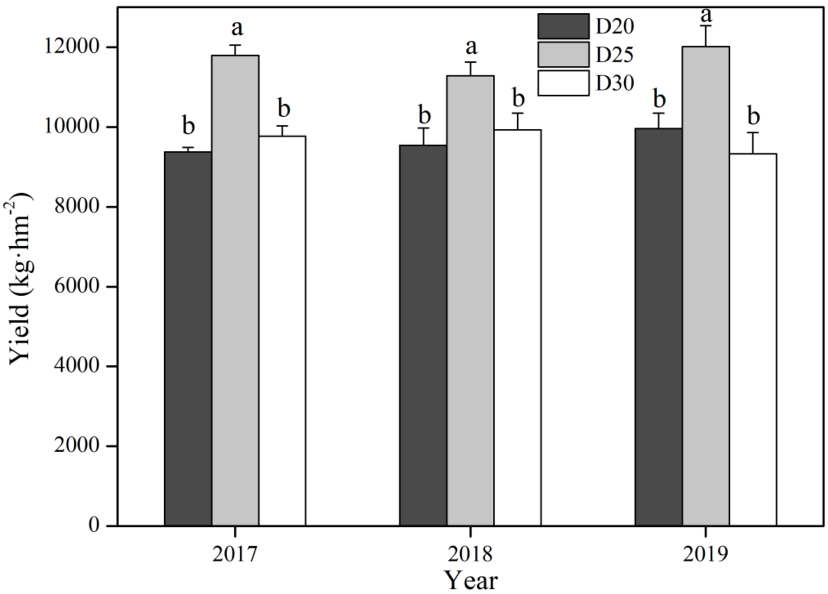

Figure 5. Yield of maize for 20 cm topsoil depth (D20), 25 cm topsoil depth (D25), and 30 cm topsoil depth (D30) in 2017, 2018 and 2019.

3.3. Water consumption and water use efficiency

Water consumption of D25 was higher than 300 mm, and significantly higher than that of D20 and D30 (Figure 6). Water consumption of D25 was higher 10.12% and 6.61% than that of D20 and D30, respectively. There was no significant difference between D20 and D30. In the three years, water consumption for the same treatment was no significant difference.

Tillage depth significantly affected water use efficiency, and for D25 the water use efficiency was significantly higher than that for D20 and D30 (Figure 7). The average water use efficiency for D20 significantly increased 5.78% and 5.88% than that for D20 and D30 in the three years. The water use efficiency was the specific value of water consumption divided by yield. The trend of water use efficiency was influenced by yield and water consumption, and was similar to the trend of yield and water consumption.

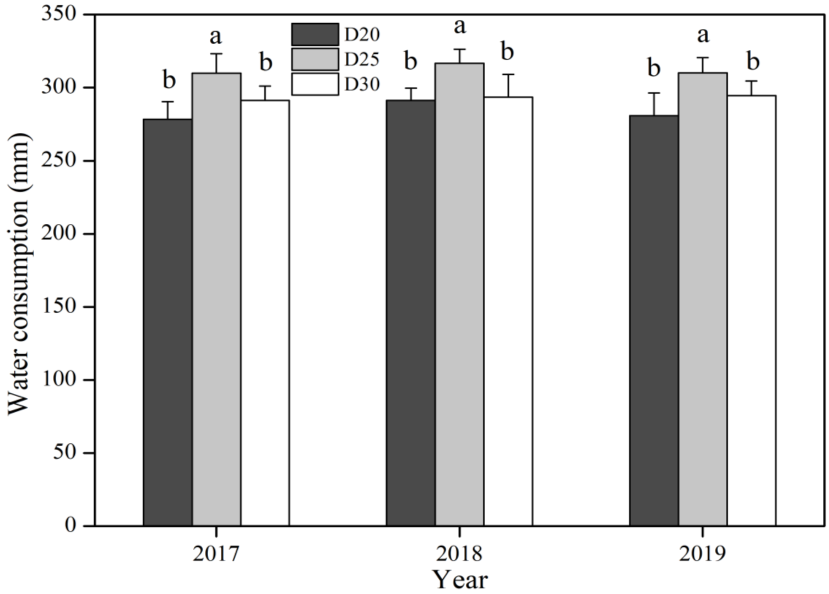

Figure 6. Water consumption in the growth period of maize for 20 cm topsoil depth (D20), 25 cm topsoil depth (D25), and 30 cm topsoil depth (D30) in 2017, 2018 and 2019.

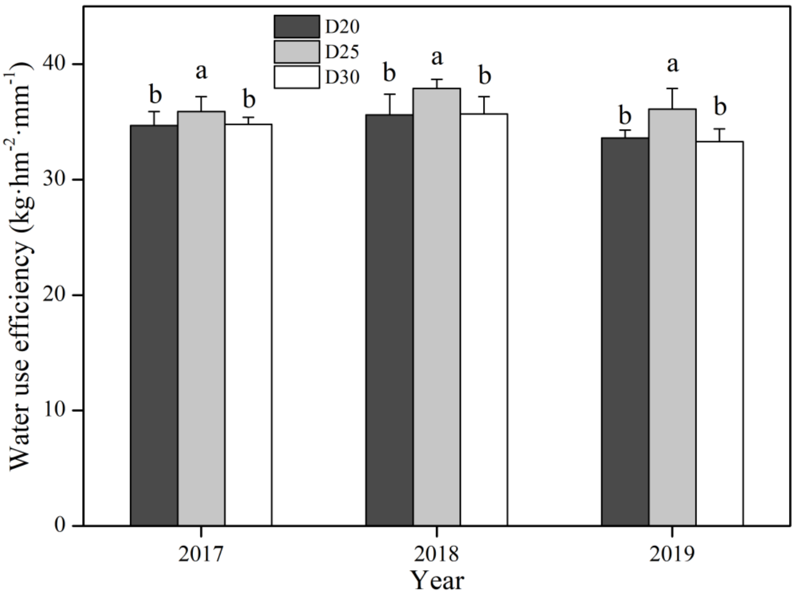

Figure 7. Water efficiency in the growth period of maize for 20 cm topsoil depth (D20), 25 cm topsoil depth (D25), and 30 cm topsoil depth (D30) in 2017, 2018 and 2019.

3.4. Total nitrogen, total phosphorus and total kalium in pre-sowing

Total nitrogen (TN), total phosphorus (TP) and total kalium (TK) are the three main nutrients in the soil. Total nitrogen in 0-20 cm depth was significantly affected by tillage depth in the three years (Figure 8A). Total nitrogen for D20 was highest in the three treatments, and decreased with the increase of tillage depth. Total phosphorus in 0-20 cm depth was significantly affected by tillage depth in 2018, however, there was no significant difference in 2017 and 2019 (Figure 8B). Total kalium in 0-20 cm depth was significantly affected by tillage depth in 2018 and 2019, whereas no significant difference in 2017 (Figure 8C). The results indicated that total nitrogen was more susceptible to the effects of tillage than total phosphorus and total kalium.

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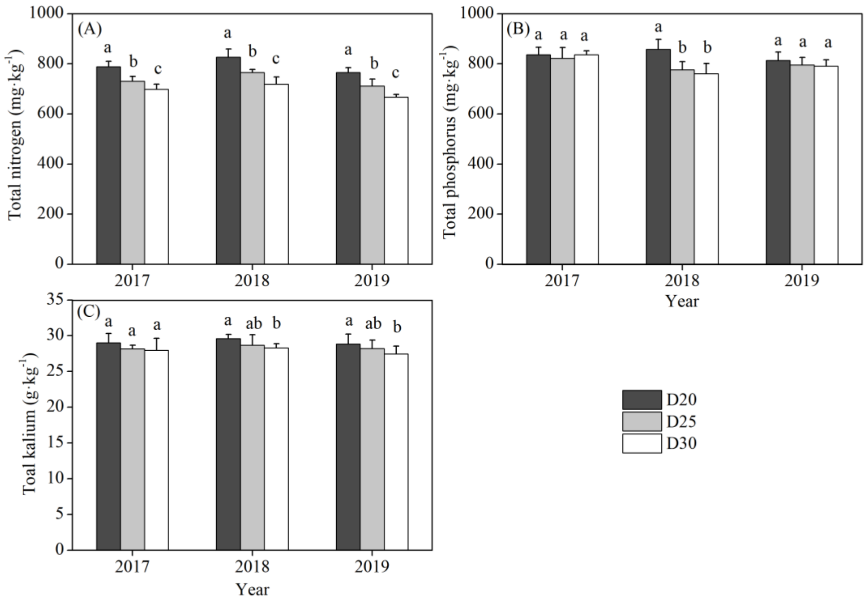

Figure 8. Total nitrogen, total phosphorus, and total kalium in 0-20cm depth before the sowing of maize for 20 cm topsoil depth (D20), 25 cm topsoil depth (D25), and 30 cm topsoil depth (D30) in 2017, 2018 and 2019.

3.5. Nonmetric multidimensional scaling (NMDS) and Structural equation models (SEM)

NMDS analysis was based on Bray-Curtis distance, the stress was 0.002, and the total explained variation was 92.69% (82.59%+10.10%) (Figure 9). The results revealed that the three treatments could be divided into three groups on the basis of tillage depth, was obviously different from each others, and tillage depth distinctly affected field capacity, soil bulk density, plow pan thickness, TN, TK and TP. Tillage depth had a obvious positive correlation withe field capacity. Yield, water use efficiency, photosynthetic rate and water consumption had a obvious positive correlation with each others which clustered together. Soil bulk density, plow pan thickness, TN, TK and TP had a obvious negative correlation with tillage depth and field capacity. In addition, yield, water use efficiency, photosynthetic rate and water consumption were higher for D25 than that for D20 and D30; soil bulk density, TN, and TK were higher for D20 than that for D25 and D30.

SEM analysis was used to analyze the major influence factors on yields and explain the contributions of different factors ($P = 0.298$, $GFI = 0.999$, and $RMSEA = 0.056$) (Figure 10). Results showed that tillage significantly directly contributed to the reduction of total nitrogen, photosynthesis and yields ($\lambda = -0.843$***, -1.443*** and −0.591*). Then, tillage had positive influences on water consumption ($\lambda = 0.286$). Total nitrogen significantly directly negatively impacted photosynthesis ($\lambda = -1.514$***), while water consumption significantly directly positively impacted photosynthesis ($\lambda = 0.252$*). The increased water consumption positively contributed to the increase of yields ($\lambda = 0.864$***), while the photosynthesis had no positive influence on the yields. The standardized total effects of tillage, total nitrogen, photosynthesis and water consumption on yields were 0.019, -0.628, 0.121, and 0.895***, respectively.

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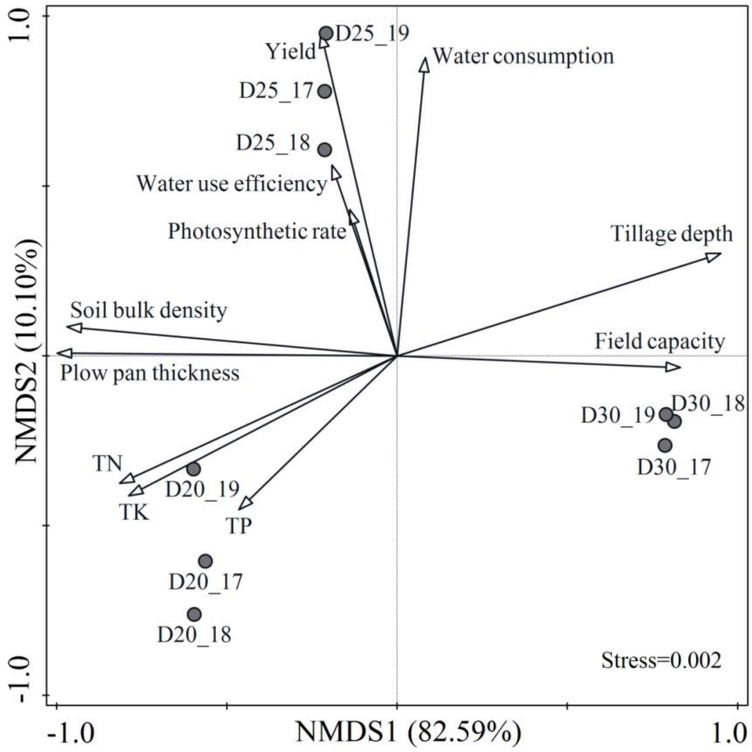

Figure 9. Nonmetric multidimensional scaling (NMDS) among the eleven factors for the three treatments in 2017, 2018 and 2019.

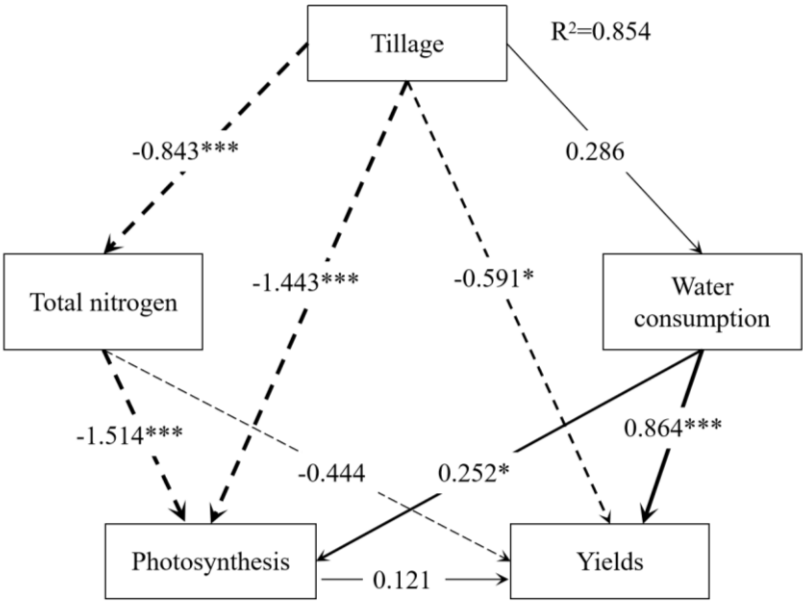

Figure 10. Structural equation models (SEM) showing the effects of tillage, total nitrogen, water consumption, photosynthesis on yield. Continuous and dashed arrows indicate positive and negative relationships respectively, and numbers adjacent to the arrows represent path coefficients λ.

4. Discussion

4.1. Responses of bulk density and field capacity to tillage depths

In this three-year study, the effects of tillage depths or different plow pan thickness on soil bulk density and field capacity were conducted. The soil tillage management can affect chemical and physical soil properties, including soil bulk density and soil water balance [27, 28]. Tillage practices can temporarily loosen soil forming macro-pores, and improve aeration and alleviate the compaction of soil, which resulted in decline of soil bulk density [22, 27]. The soil bulk density in 0 - 10 cm soil layer was lower than that in 10 -20 cm and the other soil layer because of the tillage; it declined with the depths of tillage in 10 - 20 cm and 20 - 30 cm soil layer, which was due to the tillage practices breaking up the plow pan in the 15 - 30 cm soil layer in this study (Figure 2). Reducing the soil bulk density could make roots easily extend and penetrate into deeper soil depths for absorbing water and nutrients [22]. In 30 - 60 cm soil layer, the soil bulk density was no obvious difference among different tillage depths, because of no tillage in this soil layer.

The field capacity was negatively related to the soil bulk density, and highest in 0 - 10 cm soil layer among the four soil layer in this study. The field capacity of 0.4 - 0.6 m3·m-3 in 0 - 10 cm soil layer was much higher than that (0.27 $m^3·m^{-3}$) in the study of Tesfahunegn [29]. The soil pore was small or sparse, and then the soil bulk density was high or the soil was compact; the less soil pore space resulted in less water hold up by soil, and soil water retention capacity decreased. Breaking up the plow pan was an effective measure for loosening the soil and increasing soil water retention capacity [30]. Precipitation is mostly concentrated in maize growth season in the North China Plain and some of rainfall were short but very intense (Figure 1), so partial loss of rainfall occurs frequently by runoff. The improvement of field capacity can increase soil water retention capacity, and preserve runoff from heavy rainfall. Loosening soil and increasing field capacity was an important measure for the retention of soil moisture. Some reports showed that tillage improved soil physical properties and accordingly played a vital influence on the crop growth and yields [31, 32]. Rotary tillage (depths of 15 -20 cm) increased the evaporation of soil water from the soil surface [33], however, other research reported that the evaporation in subsoiling was significantly higher than that rotary tillage [34]. These were may attributed to the plow pan impeding the soil water infiltration, and the reduction of soil bulk density increasing the soil pore, which resulted in the increase of evaporation. Therefore, plow pan and soil bulk density maybe need to maintain a appropriate degree for soil water retention and reducing the evaporation.

4.2. Responses of photosynthetic rate, water use and yield to tillage depths

Photosynthetic rate is an important factor for increasing crop yields [24], and taking necessary steps to guarantee maize production after silking plays an important role in obtaining high grain yield [1]. In this study, photosynthetic rate in bell and silking was higher for D25 than that for D20 and D30, resulted in higher maize yields (Figure 4). Greater photosynthetic rate for D25 could be attribute to the increase of soil water consumption that enhanced maize water use efficiency. This result was consistent to previous reports that the improvement of soil water availability increased the photosynthetic rate [35]. A good soil water condition is fundamental for achieving a high and sustainable crop yields [36], and increasing soil water consumption could improve crop yields [37], which was similar to this study. Water use efficiency is related to soil water consumption and crop yields. The greater photosynthetic rate could improve soil water consumption to accumulate more photosynthetic product, resulting in greater maize yields and water use efficiency. Soil tillage was an important factor for maize yields [38], and depth of 25 cm improved the maize yields in this study. Some reports showed that about 60 - 70% of root mass of crops grown in 0 - 30 cm soil layer [22, 39], and loosening the depth of 0 -30 cm soil layer could improve root to absorb more water and nutrients, resulted in more water consumption for D25 than that for D20. However, depth of 30 cm may promote the soil water and nutrients in 0 - 30 cm soil layer to permeate into deeper soil layer, which decreased the water consumption and nutrient uptake of root. These results may be because that depth of 25 cm loosened the topsoil and broke up part of plow pan, which reduced the evaporation and increased soil water consumption, photosynthetic rate and nutrient uptake, resulted in maize yields. The results were consistent with the results of SEM (Fig. 10), the total effect of water consumption on yields was highest for the four factors (λ = 0.885), and the total effect of tillage on yield was 0.019. Therefore, higher depths of tillage did not increase the maize yields, and reasonable depth of tillage need to be maintained.

4.3. Responses of soil nitrogen, phosphorus and kalium to tillage depths

Soil nutrients (including nitrogen, phosphorus and kalium) are one of the most important factors impacting soil health and crop productivity [40]. Improving available phosphorus and nitrogen in 0 - 20 cm soil layer was beneficial for improving soil quality, crop yields and water use efficiency [37]. Nitrogen fertilizer is important in agronomic practices, and supplying nitrogen fertilizer could obtain high maize yields under low nitrogen conditions [41, 42]. The same nitrogen fertilizer mass was conducted in the three treatments in this study, however, the total nitrogen in 0 - 20 cm soil layer decreased with the increase of depths. This was because loosening the 20 - 30 cm soil layer improved the nitrogen permeate into deeper soil layer form 0 - 20 cm soil layer. Phosphorus has poor mobility resulted in no difference for the three treatments, while kalium trend was similar to that of nitrogen (Fig. 8). Subsoiling broke up the plow pan, and promoted root penetration to absorb more nutrients in the deeper soil layer [24]. However, reducing nitrogen leaching into deeper soil layer was important for increasing the crop yields [43]. The maize yields for D25 was higher than that for D30, which was may attribute to the more nitrogen leaching of D30. Subsoiling could increase the maize yield, which was different from this study [19, 24]. Because about 60 - 70% of root mass of crops grown in 0 - 30 cm soil layer, breaking up the plow pan in 20 - 30 cm soil layer resulted in more water and nutrients leaching into deeper soil layer (higher than 30 cm). Moreover, on the one hand the plow pan of 5 cm and the tillage depth of 25 cm could reduce the soil water and nutrients leaching through the plow pan compared to D30. On the other hand it could improve the root uptake for water and nutrients in the 0 - 20 cm soil layer compared to D20. That was the reason that D25 had the higher soil water consumption, photosynthetic rate, maize yields and water use efficiency than D20 and D30.

5. Conclusions

This study demonstrated the tillage depth of 25 cm can improve photosynthetic rate, water consumption and maize yields. The soil bulk density, total nitrogen decreased with the increase of depths of tillage, while maize yields increased with the increase of photosynthetic rate and soil water consumption. Tillage indirectly impacted maize yields by photosynthetic rate and soil water consumption. The plow pan of 5 cm and the tillage depth of 25 cm for D25 could reduce the soil water and nutrients leaching through the plow pan. Therefore, D25 improved photosynthetic rate and soil water consumption, resulted in the increase of maize yields.

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