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# Yield benefit and soil fertility improved by different fertilizer application placements and supplementary organic manure in Maize (*Zea mays* L.)

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**ABSTRACT**: Through a long-term micro-area positioning experiment (2006-2017), the precise fertilization locations of spring maize (*Zea mays* L.) in Jilin, China, were investigated using an embedded cement bucket pot. The effects of different fertilization placements and additional application of organic manure on maize yield, biomass, grain nutrient uptake, and soil fertility were examined. Six treatments were designed: base fertilizer + topdressing shallow application ($BF_1TD_1$); base fertilizer deep + topdressing shallow application ($BF_2TD_1$); base fertilizer + topdressing deep application ($BF_1TD_2$); base fertilizer deep + topdressing deep application ($BF_2TD_2$); base fertilizer + topdressing + organic manure shallow application ($BF_1TD_1$ + OS); and base fertilizer + topdressing shallow application + organic manure deep application ($BF_1TD_1$ + OD). After 12 years of continuous experimentation, the findings revealed that $BF_2TD_2$, $BF_1TD_1$ + OS, and $BF_1TD_1$ + OD exhibited 10.59 %, 25.17 %, and 29.34 % higher average yields than $BF_1TD_1$, respectively. Deep topdressing was more beneficial in increasing maize yield and nutrient accumulation, and additionally, increasing the use of organic fertilizer enhanced plant biomass and nutrient uptake. Over the 12 years considered, the soil organic matter in the 0-20 cm and 20-40 cm layers increased by 45.96 % and 80.61 %, respectively, and the soil pH increased from 0.38 to 0.48. In general, the deep application of organic manure was more beneficial for soil retention as it can increase soil fertility in the 0-40 cm layer. Considering the high yield and nutrient absorption and utilization of maize, technical advancement for soil fertilizer in whole-field tillage layers was crucial.

**Keywords**: NPK, maize yield, nutrient absorption, pH, soil nutrient

## Introduction

Agricultural practices incur environmental costs, including greenhouse gases (Hou et al., 2021; Liu et al., 2022), ozone layer destruction (Jiao et al., 2022), groundwater pollution (Megdal, 2018), acid rain (Debnath et al., 2018), and biodiversity loss (Fanin et al., 2018). To promote sustainable yield and reduce environmental costs, Chinese smallholder farmers have utilized improved management practices (Cui et al., 2018) and increased organic fertilizer usage. However, the expenses and requirements for a larger labor force have reduced the enthusiasm of farmers (Cai et al., 2018). Chemical fertilizers increase crop yield in the short term, but they barely sustain soil fertility and even reduce it (Jiang et al., 2018; Schjoerring et al., 2019; Du et al., 2021; Grandy et al., 2022). In crop fertilizer management technologies, the fertilization site is as crucial as the quantity and ratio of fertilization (Saïdou et al., 2018; Lu et al., 2019). Different application placements can affect soil and plant nutrient uptake (Nguyen et al., 2018; Yong et al., 2018). Fertilizer application at a depth of 15-20 cm has been found to play a crucial role in increasing crop nutrient and nitrogen (N) utilization rate, enhancing soil N supply capacity, and promoting dry matter accumulation and N absorption in China (Ke et al., 2018; Mi et al., 2018b). Long-term fertilizer location tests can provide scientific guidance for fertilization (Zhang et al., 2018). Most of the above studies focused on the fertilizer application location in a specific period (Liu et al., 2019) or on the type of fertilizer (Zhang et al., 2019c). Mechanized fertilizer application has become common recently (Yang et al., 2018). It is crucial to consider the effect of fertilizer application location on maize growth and nutrient uptake during the key fertilizer application periods in the growing season.

Modern agriculture has greatly popularized mechanical fertilizer applications. It is crucial to investigate the effect of fertilizer application sites on maize growth and nutrient uptake during the two critical fertilizer application phases in the maize growing seasons, the pre-sowing and jointing stages. This research aimed to enhance and automate agronomic methods for accurate maize fertilization to ensure food security, environmentally friendly agricultural practices, and the sustainable utilization of organic fertilizer. To achieve this, the study conducted 12-year cement bucket experiments using pots to systematically examine the effects of various fertilizer application placements and organic manure fertilizer application on maize yield, plant nutrient accumulation, and soil nutrients in the black soil region of central northeast China, and to provide scientific guidance for fertilization in this region, support improvement in fertilizer application machinery, and establish a scientific foundation for enhancing farmland productivity of black soil areas.

## Materials and Methods

### Overview of the study area

The ongoing field experiment commenced in the spring of 2006, in Gongzhuling City, Jilin Province, northeast China (43°29′55″ N, 124°48′43″ E, altitude 120 m). The region is characterized by a temperate continental monsoon climate featuring cold winters, high temperatures, and rainy summers. The average annual precipitation is 600 mm, and it has had an average rainfall of 477.38 mm from May to Sept over the past 20 years. The average annual temperature is 5.6 °C, the frost-free period lasts 125-140 days, and the effective accumulated temperature ranges from 26 °C to 30 °C. Prior to the experiment, soil samples were collected from a depth of 0-40 cm in the nursery on 28 Apr 2006. The experimental field was a typical black soil according to the Chinese Soil Classification System, classified as a fine-silty, mixed mesic typical Hapludolls according to the United States Department of Agriculture classification system (USDA). The soil texture was 31.6% clay, 39.5% silt, and 28.9% sand and the 0-20 cm layers were characterized by pH 6.10, 29.8 g $kg^{-1}$ organic matter, 138.82 mg $kg^{-1}$ available N, 57.94 mg $kg^{-1}$ available phosphorus (AP), 192.85 mg $kg^{-1}$ available potassium (AK) in the 0-20 cm layers. The 20-40 cm layers were characterized by pH 6.79, 22.0 g $kg^{-1}$ organic matter, 125.41 mg $kg^{-1}$ available N, 32.70 mg $kg^{-1}$ AP, and 170.43 mg $kg^{-1}$ AK.

The monthly rainfall data during the maize growth period from 2006 to 2017 are shown in Figure 1. In this study, the annual rainfall years were categorized according to the dryness index (DI) (Liu et al., 2021). DI was calculated using the formula DI = (P-M)/σ, DI $< -0.35$ indicates a drought year, $-0.35 \leq DI \leq 0.35$ indicates a typical water year, DI $> 0.35$ indicates a wet year, P represents the rainfall during the maize growth period of the current year (mm), and M the average rainfall during the multi-year maize growth period (mm) (May-Sept). In the drought years of 2006, 2007, 2009, 2011, 2014, and 2015, average precipitation during the maize growth period was 334.0 mm, and DI was −1.11. Notably, the precipitation in 2014 was 420.2 mm, and the rainfall during the growth period from May to Sept was relatively uniform. Average rainfall during the growth period of maize in 2017 was 513.0 mm, and DI was 0.30, which indicates a typical water year. Rainfall was evenly distributed in May, June, and Sept, while the flowering and grain-filling periods of maize were from July to Aug. In the years of abundant rainfall, including 2008, 2010, 2012, 2013, and 2016, average precipitation during the maize growth period was 571.4 mm, and DI was 0.73, which indicates a wet year. In 2010, the maize jointing stage experienced drought conditions, while 2012-2013 was characterized by less rainfall during the maize seedling stage.

### Experimental design

The experiment involved in situ potted plants, with soil embedded in hollow cement buckets measuring 70 cm in diameter, covering an area of 0.385 $m^2$. The variety tested was Xianyu 335, and three maize seeds were sown in each pot, with a density equivalent to 78,000 plants $ha^{-1}$. The experimental design consisted of two factors: base fertilizer position and topdressing position. For each factor, two application depths were used: shallow (10 cm away from the upper edge of the cement bucket) and deep (30 cm away from the upper edge of the cement bucket). Additionally, organic manure was applied in both the shallow application (OS) and the deep application (OD), resulting in a total of six treatments, and each treatment was repeated three times. The base fertilizer was applied before sowing, with N fertilizer at a rate of 110 kg $ha^{-1}$ (5.0 g urea per pot), P-based fertilizer ($P_2O_5$) at a rate of 138 kg $ha^{-1}$ (11.4 g diammonium phosphate per pot), and K-based fertilizer ($K_2O$) 126 kg $ha^{-1}$ (8.0 potassium chloride g per pot). Topdressing was conducted at the corn jointing stage, with N applied at a rate of 250 kg $ha^{-1}$ (21 g urea per pot) and organic fertilizer at 30000 kg $ha^{-1}$ (1200 g per plant), applied together with the basal fertilizer. The root stubble was left in the field every autumn. The N fertilizers used were all urea (N 46 %), the phosphate fertilizers all diammonium phosphate (N 18 %, $P_2O_5$ 46 %), and the K fertilizers potassium chloride ($K_2O$ 60 %). The pH, soil organic matter (SOM), total nitrogen

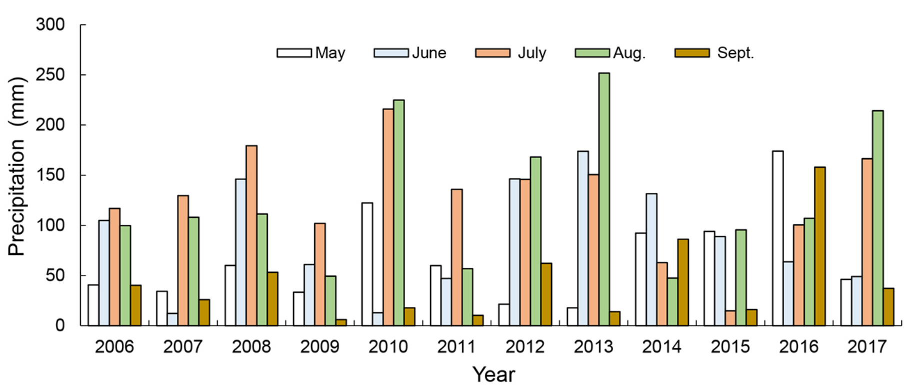


**Figure 1** – Precipitation in the experiment field during maize growth stages from 2006 to 2017.

(TN), total phosphorus (TP), and total potassium (TK) in the organic fertilizer (cattle manure) were 8.9, 302, 20.3, 5.3, and 9.7 g kg$^{-1}$, respectively. The seeds were sown in early May and harvested in late Sept. The actual shot and schematic diagram of the pot experiment are shown in Figure 2, and the details of the experimental treatment are in Table 1.

### Sample collection and determination

Soil samples at depths of 0-20 cm and 20-40 cm were collected before sowing maize in 2006 to measure SOM, AN, AP, TK, and pH values. After the maize harvest in 2008 and 2016, soil samples at depths of 0-20 cm and 20-40 cm were collected. The following parameters were determined: soil organic matter (SOM); total nitrogen (TN); total phosphorus (TP) and total potassium (TK); available N (AN); available phosphorus (AP); available potassium (AK); and pH values. SOM was determined via the concentrated sulfuric acid-potassium dichromate elimination-ferrous sulfate titration method. TN by the semi-micro Kjeldahl method, TP via sodium hydroxide melting and the molybdenum-antimony anti-colorimetric method, TK via sodium hydroxide fusion-flame photometry, AN via the alkaline diffusion method, AP via sodium bicarbonate extraction and molybdenum-antimony anti-colorimetric method, AK via ammonium acetate extraction and flame photometry. The pH value of soil (water:soil = 2.5 mL:1.0 g) was measured using a composite electrode (Bao, 2000). At the mature stage of maize, all three plants in each treatment and pot were harvested, and the grain yield (calculated using drying mass) and 100-kernel weight of each plant were determined. After the harvests from 2013 to 2015, the leaves, stems (sheaths), grains, and cob organs of the plants were separated. The plants were then dried in an oven at 105 °C for 60 min, then at 75 °C until constant weight was achieved. The dried plants were crushed to determine the contents of N, P, and K via the semi-micro Kjeldahl method for TN, the sodium hydroxide fusion-molybdenum-antimony anti-colorimetric method for TP, and the sodium hydroxide fusion-flame photometry was used for TK (Bao, 2000).

### Statistical analysis

Statistical analysis was conducted with SPSS 22.0 software. One-way analysis of variance and multiple

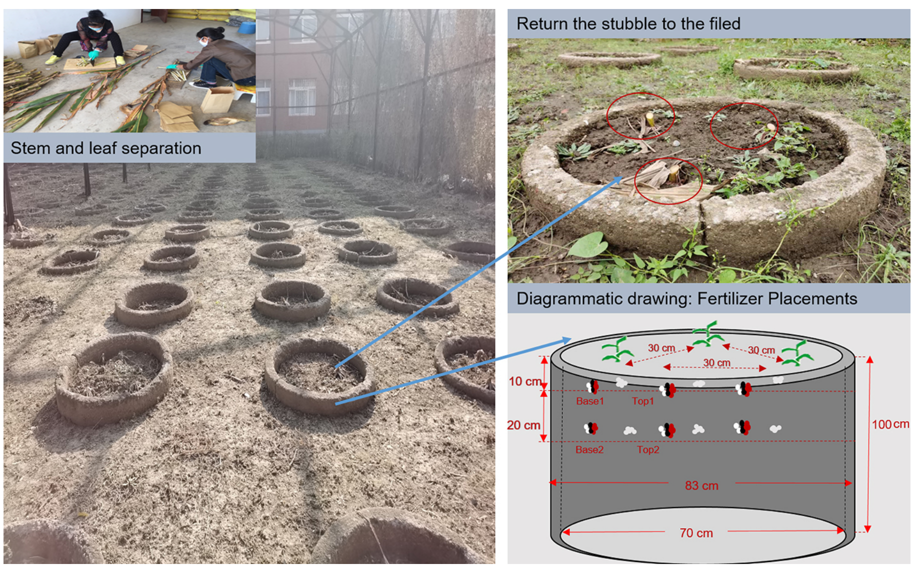


**Figure 2** – Real shot and diagrammatic drawing of pots experiment.

**Table 1** – The experiment was in situ potted plants with six treatments, the base and topdressing fertilizer location contained two levels: shallow and deep applications.

| Treatment | Base fertilizer placement (BF) | Top dressing placement (TD) |
|---|---|---|
| $BF_1TD_1$ | Shallow | Shallow |
| $BF_2TD_1$ | Deep | Shallow |
| $BF_1TD_2$ | Shallow | Deep |
| $BF_2TD_2$ | Deep | Deep |
| $BF_1TD_1$ + OS | Shallow application of organic manure and inorganic fertilizer | Shallow |
| $BF_1TD_1$ + OD | Shallow application of inorganic fertilizer + deep application of organic manure | Shallow |

Base fertilizer placement contained two horizontal shallow (0-10 cm) and deep (10-30 cm) applications, while the top dressing placement contained two horizontal shallow (0-10 cm) and deep (10-30 cm) applications. $BF_1TD_1$ was used as a control treatment. Organic manure shallow (OS) and organic manure deep (OD) application were added, for a total of six treatments. Each treatment was sown in three pots, and 3 maize seedlings were sown in each pot.

comparisons (Duncan's method) were performed. Data processing and graphing were conducted using Microsoft Excel 2016.

## Results

### Influences of different fertilization placements on maize yield and its composition

From 2006 to 2017, the average yearly yields of the five treatments ($BF_2TD_1$, $BF_1TD_2$, $BF_2TD_2$, $BF_1TD_1$ + OS, and $BF_1TD_1$ + OD) were 304.6, 321.9, 325.8, 368.7, and 381.0 g per plant, respectively (Figure 3). Compared with the $BF_1TD_1$ treatment, the yields increased by 3.40 %, 9.28 %, 10.59 %, 25.17 %, and 29.34 %, respectively. Over the 12 years considered, the $BF_1TD_1$ + OS and $BF_1TD_1$ + OD treatments had the highest yields, followed by the $BF_2TD_2$ treatment. In the early stage, from 2006 to 2008, the yield of the $BF_1TD_1$ treatment was only marginally higher than that of the $BF_2TD_1$ treatment. The yields of the six treatments in the first three years differed slightly ($p$ > 0.05). Since 2009, the order of maize yield has been $BF_2TD_2$ > $BF_1TD_2$ > $BF_2TD_1$ > $BF_1TD_1$, which indicates that different fertilizer application placements directly impact fertilizer efficiency and crop yield levels. Throughout the 12 years, the application of organic fertilizer increased owing to the shallow fertilizer application. Only the yields in 2006, 2010, and 2011 demonstrated that $BF_1TD_1$ + OS > $BF_1TD_1$ + OD. In other years, the yield of deep application of organic manure was superior to that of shallow application. This illustrates that using organic manure can increase maize output, with deep fertilization partially important. The yield contained a sizeable portion of the 100-kernel weight. The average yearly 100-kernel weights of the fertilization positions for $BF_2TD_1$, $BF_1TD_2$, $BF_2TD_2$, $BF_1TD_1$ + OS, and $BF_1TD_1$ + OD were higher than that of the $BF_1TD_1$ treatment, by 0.91 %, 1.96 %, 3.20 %, 4.90 %, and 7.87 %, respectively. The consistent yields further demonstrated the effectiveness of deep fertilization (Figure 4). The yearly rainfall

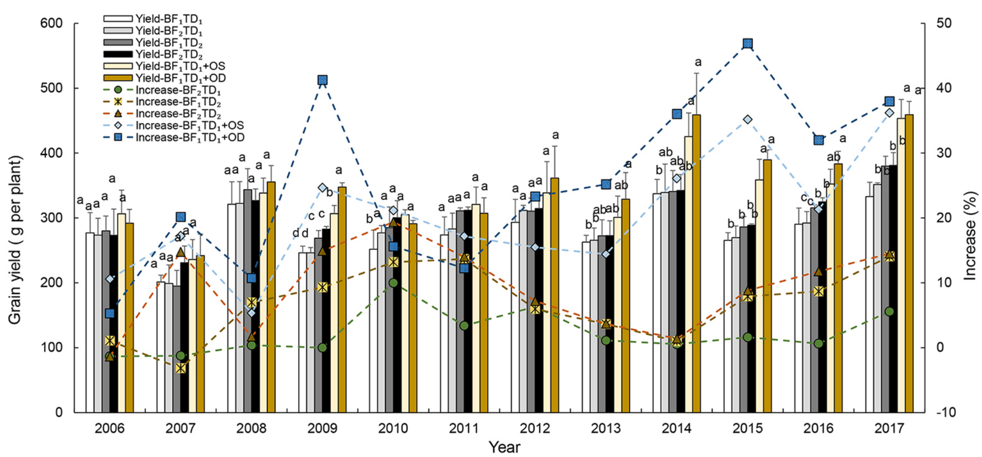


**Figure 3** – Maize yield and its increase rate under different fertilizer placements from 2006 to 2017. Values followed by different small letters in one column in the same year indicate differences between treatments at 0.05 level (Duncan's method). The increase rate was determined by comparing BF1TD1 with other treatments.

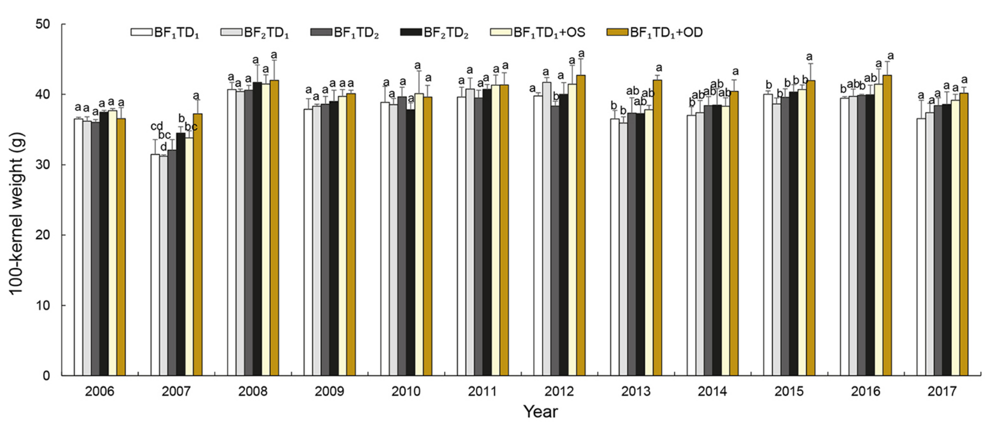


**Figure 4** – 100-kernel weight of different fertilizer placement from 2006 to 2017. Values followed by different small letters in one column in the same year indicate differences between treatments at 0.05 level (Duncan's method).

pattern determined by DI can be used to assess maize production and its yield composition (Table 2). In the drought years, the yield of $BF_2TD_1$, $BF_1TD_2$, $BF_2TD_2$, $BF_1TD_1$ + OS, and $BF_1TD_1$ + OD increased by 0.58 %, 5.07 %, 8.06 %, 22.05 %, and 27.46 %, respectively, and the 100-kernel weight of $BF_1TD_2$, $BF_2TD_2$, $BF_1TD_1$ + OS, and $BF_1TD_1$ + OD increased by 0.76 %, 3.59 %, 4.07 %, and 6.81 %, respectively, compared with the $BF_1TD_1$ treatment. In plain water years, the yields of $BF_2TD_1$, $BF_1TD_2$, $BF_2TD_2$, $BF_1TD_1$ + OS, and $BF_1TD_1$ + OD increased by 5.58 %, 14.07 %, 14.48 %, 36.18 %, 37.96 % and the 100-kernel weight of $BF_2TD_1$, $BF_1TD_2$, $BF_2TD_2$, $BF_1TD_1$ + OS, and $BF_1TD_1$ + OD increased by 2.28 %, 5.01 %, 5.47 %, 7.11 %, 9.85 % compared with the $BF_1TD_1$ treatment. In wet water years, the yields of $BF_2TD_1$, $BF_1TD_2$, $BF_2TD_2$, $BF_1TD_1$ + OS, and $BF_1TD_1$ + OD increased by 3.51 %, 7.61 %, 8.41 %, 15.19 %, and 21.21 %, while the 100-kernel weight of $BF_2TD_1$, $BF_1TD_2$, $BF_2TD_2$, $BF_1TD_1$ + OS, and $BF_1TD_1$ + OD increased by 0.47 %, 0.22 %, 0.70 %, 3.60 %, and 7.01 %, respectively, compared with the $BF_1TD_1$ treatment. The treatment, the year, and their interactions substantially influenced the yield and 100-kernel weight (Table 2). Multiple applications of organic manure, particularly deep applications, greatly improved yield and composition compared with single applications of inorganic fertilizer.

### Impacts of different fertilization placements on plant nutrient uptake and distribution

Organic fertilizer application had a considerable impact on maize biomass (Figure 5). In 2013, the biomass of maize in $BF_2TD_{1,}$ $BF_1TD_2$, $BF_2TD_2$, $BF_1TD_1$ + OS, and $BF_1TD_1$ + OD increased by 1.78 %, 2.00 %, 3.63 %, 9.45 % and 14.26 %, respectively, compared with the $BF_1TD_1$ treatment. The increases were 5.88 %, 7.59 %, 7.89 %, 32.71 %, and 43.43 % in 2014, and 4.27 %, 6.61 %, 8.24 %, 19.74 %, and 26.39 % in 2015, respectively, compared with the $BF_1TD_1$ treatment. In the wet year (2013), only the deep application of organic manure massively increased maize biomass ($p$ < 0.05). In the dry years (2014, 2015), both the deep and shallow applications of organic manure increased maize biomass. The biomass of maize from 2013 to 2015 followed the order $BF_1TD_1$ + OD > $BF_1TD_1$ + OS. These findings suggest that the comprehensive application of organic manure can greatly increase soil fertility and buffering effectiveness, ensure stable high maize production in both wet and dry years, and reduce soil erosion.

Owing to nutrient absorption in grain and straw from 2013 to 2015 (Figures 6-8), N and P predominantly accumulated in the grains, accounting for 70.2 %-80.8 % of the total N accumulation and 60.0 %-67.1 % of the total P accumulation, respectively. There was

**Table 2** – The grain yield and 100-kernel weight in response to different fertilizer placements according to the dryness index (DI) from 2006 to 2017.

| Rainfall year types | yield (g per plant) | | | | | | 100-kernel weight (g) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $BF_1TD_1$ | $BF_2TD_1$ | $BF_1TD_2$ | $BF_2TD_2$ | $BF_1TD_1$ + OS | $BF_1TD_1$ + OD | $BF_1TD_1$ | $BF_2TD_1$ | $BF_1TD_2$ | $BF_2TD_2$ | $BF_1TD_1$ + OS | $BF_1TD_1$ + OD |
| Dry year (DI < –0.35) | 266.84 bc | 268.39 bc | 280.38 b | 288.35 b | 325.69 a | 339.55 a | 37.08 b | 37.08 b | 37.36 b | 38.41 ab | 38.59 ab | 39.60 a |
| Normal year (–0.35 ≤ DI ≤ 0.35) | 332.92 b | 351.49 b | 379.76 b | 381.12 b | 453.37 a | 459.30 a | 36.57 a | 37.40 a | 38.40 a | 38.57 a | 39.17 a | 40.17 a |
| Rainy year (DI > 0.35) | 283.92 b | 293.87 b | 305.52 b | 307.78 b | 327.04 ab | 344.15 a | 39.07 c | 39.25 bc | 39.15 bc | 39.34 bc | 40.47 b | 41.81 a |
| Mean | 294.56 c | 304.59 bc | 321.89 ab | 325.75 b | 368.70 a | 381.00 a | 37.57 d | 37.91 d | 38.31 cd | 38.77 bc | 39.41 b | 40.53 a |
| Increase (%) | - | 3.40 | 9.28 | 10.59 | 25.17 | 29.34 | - | 0.91 | 1.96 | 3.20 | 4.90 | 7.87 |
| CV (%) | 7.9 | 7.2 | 6.9 | 6.1 | 9.3 | 7.7 | 4.0 | 2.3 | 3.3 | 3.7 | 3.6 | 4.2 |

Values followed by different letters in the same line mean differences according to Duncan's method at 5 % probability.

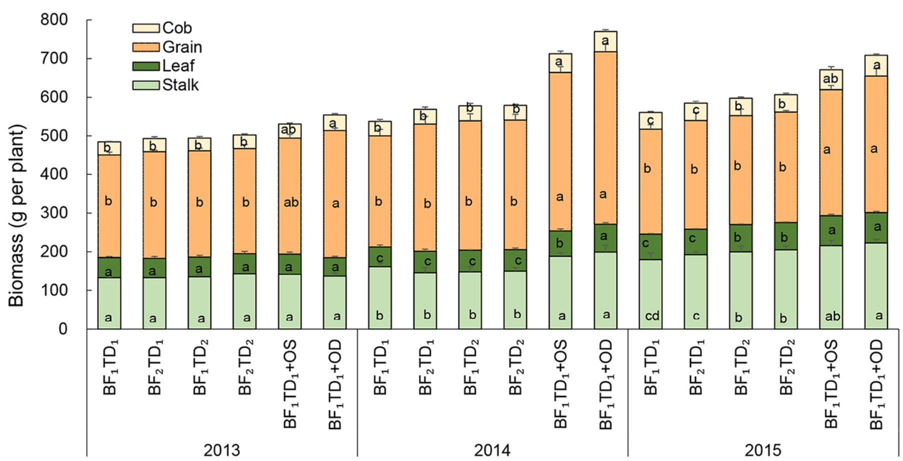


**Figure 5** – Effects of different fertilizer placement on biomass in maize from 2013 to 2015. Values followed by different small letters in one column in the same year indicate difference among treatments at 0.05 level (Duncan's method).

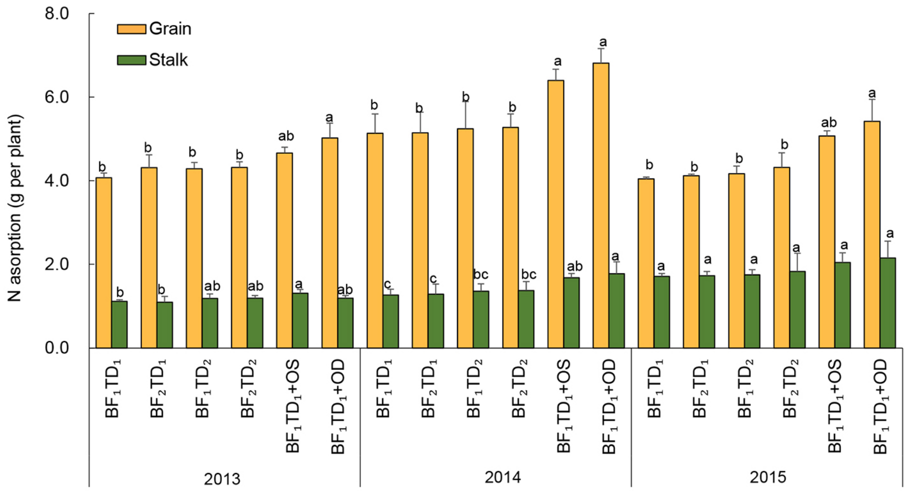


**Figure 6** – Effects of different fertilizer placement on nitrogen absorption in maize from 2013 to 2015. Values followed by different small letters in one column in the same year indicate difference among treatments at 0.05 level (Duncan's method).

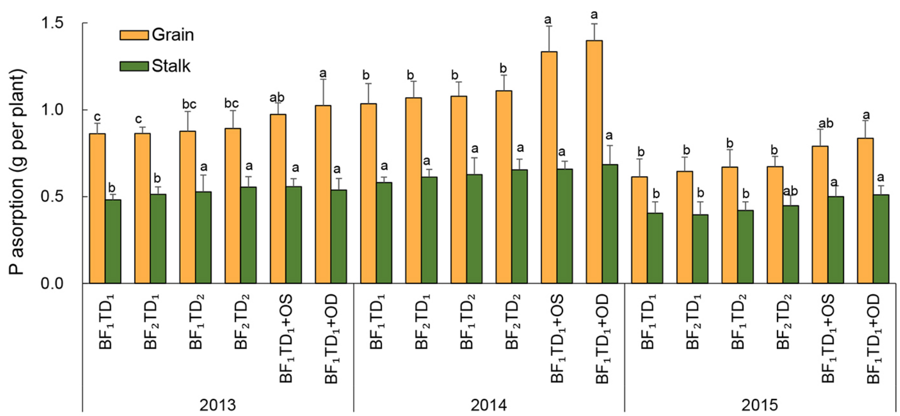


**Figure 7** – Effects of different fertilizer placement on phosphorus absorption in maize from 2013 to 2015. Values followed by different small letters in one column in the same year indicate difference among treatments at 0.05 level (Duncan's method).

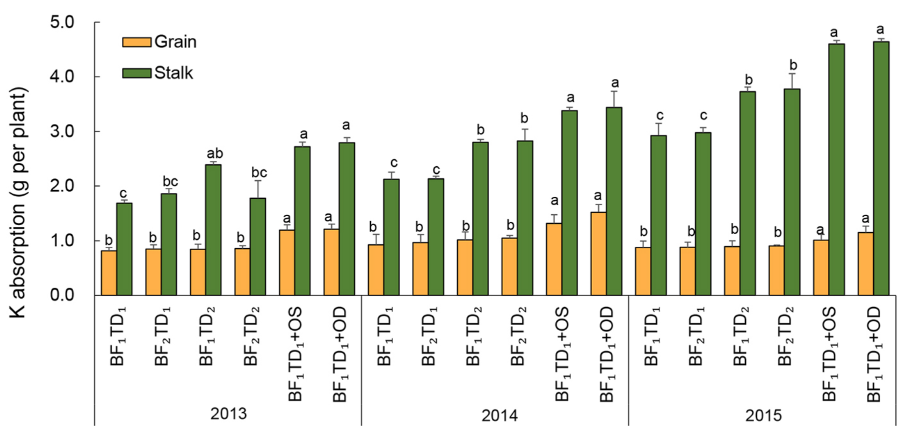


**Figure 8** – Effects of different fertilizer placement on potassium absorption in maize from 2013 to 2015. Values followed by different small letters in one column in the same year indicate difference among treatments at 0.05 level (Duncan's method).

no substantial difference in N and P accumulation in straw ($p$ > 0.05). However, most of the K accumulated in straw, and the K in grain accounted for 18.1 %-32.6 % of the total K accumulation. Compared with $BF_1TD_1$, the N uptake of the $BF_2TD_1$, $BF_1TD_2$, and $BF_2TD_2$ treatment respectively increased by 2.35 %, 3.34 %, and 4.91 %, P uptake by 2.30 %, 4.20 %, and 6.12 %, and K uptake by 3.31 %, 5.51 %, and 7.60 %. Compared with the $BF_1TD_1$

treatment, the $BF_1TD_1$ + OS treatment featured N, P, and K uptake of 21.63 %, 22.94 %, and 35.15 %, respectively, while the $BF_1TD_1$ + OD treatment featured N, P, and K uptake of 30.11 %, 29.34 %, and 48.89 %, after the application of organic manure. From the perspective of different fertilization placements, the grain N, P, and K uptake showed the following trend $BF_2TD_2$ > $BF_1TD_2$ > $BF_2TD_1$ > $BF_1TD_1$, which indicates that the deep application of basal and topdressing fertilizer could increase nutrient uptake.

Compared with the $BF_1TD_1$, in 2013, the grain N uptake of the $BF_1TD_2$, $BF_2TD_1$, $BF_2TD_2$, $BF_1TD_1$ + OS, and $BF_1TD_1$ + OD treatments respectively increased by 5.90 %, 5.41 %, 6.14 %, 14.50 %, and 23.42 %, grain P uptake by 0.27 %, 1.85 %, 3.61 %, 13.12 %, and 18.93 %, and grain K uptake by 4.08 %, 3.54 %, 4.82 %, 46.29 %, and 48.31 %. In 2014, compared with $BF_1TD_1$ treatment, the grain N uptake of the $BF_1TD_2$, $BF_2TD_1$, $BF_2TD_2$, $BF_2TD_2$, and $BF_1TD_1$ + OD treatments respectively increased by 1.92 %, 3.27 %, 6.91 %, 25.54 %, and 34.21 %, grain P uptake increased by 3.30 %, 4.22 %, 7.17 %, 28.91 %, and 35.15 %, and K uptake in grain was increased by 4.72 %, 9.87 %, 13.61 %, 42.74 %, and 64.87 %, respectively. In 2015, compared with the $BF_1$TD1 treatment, grain N uptake respectively increased by 1.92 %, 3.27 %, 6.91 %, 25.54 %, and 34.21 %, and grain P uptake by 5.31 %, 9.32 %, 9.78 %, 28.85 %, and 36.47 %. Additionally, K uptake in grain increased by 0.27 %, 1.90 %, 2.98 %, 15.66 %, and 31.40 %, respectively., Thus, the nutrient uptakes of grains of $BF_1TD_1$ + OD for the same fertilizer type were higher than $BF_1TD_1$ + OS, regardless of fertilization placement, growing season, and fertilizer type. Chemical fertilizer treatment had no appreciable effects, substantiating the fact that organic fertilizer impacted maize growth and nutrient uptake.

## Influence of different fertilization placements on soil nutrient content

During a multi-year localization test, the amounts of SOM, AP, AK, TN, TP, TK, and soil pH varied dramatically depending on the treatments (Table 3). Compared with the initial values in 2006, SOM in all treatments increased by 4.36 %-106.68 %, and SOM in the 0-40 cm soil layer increased greatly in the $BF_1TD_1$ + OS and $BF_1TD_1$ + OD treatments. Moreover, compared with the initial values, for both treatments, the SOM in the 0-20 cm soil layer increased by 49.66 % and 42.25 % (average 45.96 %), and in the 20-40 cm soil layer increased by 54.55 % and 106.68 % (average 80.61 %), respectively. These results differed the other treatments ($p$ < 0.05). Compared with

**Table 3** – Soil organic matter (SOM), available N, available P, available K, total N, total P, total K, and pH of different treatments in 0-40 cm soil layer after 3 and 11 years.

| Year | Treatment | Soil depth | SOM | Available N | Available P | Available K | Total N | Total P | Total K | pH |
|---|---|---|---|---|---|---|---|---|---|---|
| | | cm | g kg$^{-1}$ | mg kg$^{-1}$ | | | g kg$^{-1}$ | | | |
| 2008 | $BF_1TD_1$ | 0-20 | 32.6 ± 1.44 a | 125.38 ± 13.40 a | 39.28 ± 2.22 c | 196.64 ± 23.27 c | 1.60 ± 0.08 ab | 0.52 ± 0.09 a | 21.2 ± 0.21 d | 6.65 ± 0.06 c |
| | | 20-40 | 15.3 ± 0.81 bc | 67.05 ± 8.40 c | 11.8 ± 0.04 c | 141.18 ± 8.61 b | 0.88 ± 0.06 bc | 0.31 ± 0.00 ab | 21.9 ± 0.38 b | 6.77 ± 0.02 bc |
| | $BF_2TD_1$ | 0-20 | 30.1 ± 4.62 a | 126.85 ± 4.32 a | 30.3 ± 1.19 d | 196.84 ± 3.72 c | 1.54 ± 0.12 ab | 0.42 ± 0.02 b | 21.38 ± 0.22 d | 6.66 ± 0.02 c |
| | | 20-40 | 15.0 ± 0.20 bc | 75.70 ± 11.0 c | 22.71 ± 8.89 bc | 152.15 ± 2.01 b | 0.79 ± 0.04 c | 0.24 ± 0.13 b | 21.92 ± 0.14 b | 6.73 ± 0.04 bc |
| | $BF_1TD_2$ | 0-20 | 34.1 ± 1.80 a | 124.82 ± 8.76 a | 39.40 ± 3.84 c | 277.29 ± 19.82 a | 1.60 ± 0.09 ab | 0.47 ± 0.02 b | 22.58 ± 0.24 ab | 6.80 ± 0.07 c |
| | | 20-40 | 15.5 ± 1.71 c | 99.47 ± 8.16 b | 64.65 ± 12.80 a | 189.93 ± 9.51 a | 0.91 ± 0.23 bc | 0.40 ± 0.04 a | 22.93 ± 0.23 a | 6.79 ± 0.07 b |
| | $BF_2TD_2$ | 0-20 | 30.9 ± 8.43 a | 123.91 ± 12.96 a | 35.69 ± 7.32 cd | 237.47 ± 26.50 b | 1.39 ± 0.35 b | 0.41 ± 0.05 b | 22.64 ± 0.11 a | 6.66 ± 0.08 c |
| | | 20-40 | 18.8 ± 4.13 b | 77.49 ± 0.83 c | 35.87 ± 5.95 b | 177.74 ± 17.93 a | 0.87 ± 0.14 bc | 0.39 ± 0.02 a | 22.86 ± 0.21 a | 6.66 ± 0.11 c |
| | $BF_1TD_1$ + OS | 0-20 | 37.2 ± 0.72 a | 140.21 ± 9.24 a | 65.06 ± 0.68 a | 280.13 ± 11.64 a | 1.84 ± 0.06 a | 0.49 ± 0.05 b | 22.15 ± 0.21 bc | 6.6 ± 0.05 b |
| | | 20-40 | 18.3 ± 1.10 bc | 95.28 ± 6.32 b | 63.44 ± 4.36 a | 195.62 ± 12.20 a | 1.05 ± 0.02 ab | 0.40 ± 0.02 a | 22.57 ± 0.37 a | 6.69 ± 0.06 bc |
| | $BF_1TD_1$ + OD | 0-20 | 33.96 ± 1.94 a | 137.49 ± 4.17 a | 51.75 ± 1.36 b | 279.84 ± 12.67 a | 1.52 ± 0.00 b | 0.49 ± 0.02 b | 22.01 ± 0.43 c | 6.97 ± 0.09 a |
| | | 20-40 | 23.42 ± 1.52 a | 116.67 ± 5.45 a | 51.99 ± 15.7 a | 190.75 ± 14.23 a | 1.20 ± 0.12 a | 0.38 ± 0.02 a | 22.44 ± 0.34 ab | 6.96 ± 0.05 a |
| 2016 | $BF_1TD_1$ | 0-20 | 35.0 ± 0.32 b | 132.2 ± 5.93 b | 32.03 ± 4.08 b | 125.07 ± 16.62 b | 1.37 ± 0.08 b | 0.48 ± 0.10 a | 19.8 ± 0.46 b | 6.71 ± 0.03 b |
| | | 20-40 | 27.9 ± 2.11 d | 111.3 ± 8.90 b | 8.03 ± 0.52 d | 107.45 ± 2.89 c | 1.01 ± 0.03 c | 0.40 ± 0.02 c | 21.6 ± 0.26 d | 6.77 ± 0.19 d |
| | $BF_2TD_1$ | 0-20 | 32.2 ± 1.16 bc | 137.34 ± 6.53 b | 14.7 ± 3.05 d | 123.10 ± 13.29 b | 1.33 ± 0.04 b | 0.49 ± 0.04 a | 21.26 ± 0.38 a | 6.43 ± 0.05 b |
| | | 20-40 | 29.6 ± 0.71 cd | 108.08 ± 14.0 b | 12.33 ± 1.66 d | 115.31 ± 6.94 bc | 1.02 ± 0.16 c | 0.40 ± 0.03 c | 21.39 ± 0.19 cd | 6.99 ± 0.04 cd |
| | $BF_1TD_2$ | 0-20 | 32.4 ± 0.43 bc | 138.76 ± 7.98 b | 23.76 ± 1.33 c | 140.66 ± 12.4 b | 1.40 ± 0.11 b | 0.55 ± 0.02 a | 21.62 ± 0.45 a | 6.27 ± 0.09 bc |
| | | 20-40 | 28.2 ± 1.74 cd | 119.8 ± 11.91 b | 12.27 ± 1.54 bc | 120.54 ± 7.86 bc | 1.09 ± 0.06 c | 0.43 ± 0.01 c | 22.24 ± 0.12 bc | 6.91 ± 0.01 c |
| | $BF_2TD_2$ | 0-20 | 31.1 ± 2.72 c | 136.64 ± 17.96 b | 20.28 ± 1.75 cd | 133.39 ± 3.69 b | 1.33 ± 0.12 b | 0.44 ± 0.04 a | 21.86 ± 0.19 a | 6.16 ± 0.05 c |
| | | 20-40 | 25.7 ± 1.51 c | 98.28 ± 13.98 b | 7.75 ± 0.66 bc | 110.93 ± 6.86 bc | 0.98 ± 0.10 c | 0.39 ± 0.02 c | 22.36 ± 0.25 bc | 7.05 ± 0.06 bc |
| | $BF_1TD_1$ + OS | 0-20 | 44.6 ± 1.70 a | 187.88 ± 12.74 ab | 51.62 ± 4.25 a | 185.64 ± 15.6 a | 2.03 ± 0.06 a | 0.76 ± 0.03 b | 21.71 ± 0.16 a | 6.30 ± 0.08 bc |
| | | 20-40 | 34.0 ± 2.54 b | 182.84 ± 29.41 a | 20.70 ± 7.19 b | 126.22 ± 5.61 b | 1.42 ± 0.13 b | 0.51 ± 0.06 b | 21.74 ± 0.48 bc | 7.17 ± 0.03 ab |
| | $BF_1TD_1$ + OD | 0-20 | 42.39 ± 2.8 a | 235.76 ± 73.64 a | 51.83 ± 7.70 a | 142.38 ± 10.3 b | 1.96 ± 0.05 a | 0.75 ± 0.03 b | 21.71 ± 0.40 a | 6.39 ± 0.02 bc |
| | | 20-40 | 45.47 ± 2.5 a | 178.2 ± 23.88 a | 41.3 ± 12.0 a | 173.48 ± 15.2 a | 2.06 ± 0.18 a | 0.77 ± 0.00 a | 21.51 ± 0.76 a | 7.27 ± 0.04 a |

Values followed by different small letters indicate differences between treatments in the same year at the same soil depth at 0.05 level (Duncan's method). SOM = Soil organic matter; N = nitrogen; P = phosphorus; K = potassium.

the levels in 2006, only the $BF_1TD_1$ + OS and $BF_1TD_1$ + OD treatments enhanced the AN levels in the 0-40 cm soil layer, with a 35.34 % and 69.83 % increase in the 0-20 cm soil layer and a 45.79 % and 26.15 % increase in the 20-40 cm soil layer, respectively. However, the other treatments and soil layers exhibited decreases, and the differences were expressive ($p < 0.05$). The AP and AK content in the 20-40 cm soil layer increased by 26.30 % and 1.79 % in the $BF_1TD_1$ + OD treatment compared with the contents in 2006, while the $BF_1TD_1$, $BF_1TD_2$, $BF_2TD_1$, $BF_2TD_2$, $BF_1TD_1$ + OS, and $BF_1TD_1$ + OD treatments exhibited decreases of 10.55 %-76.30 % and 3.74 %-36.95 %, respectively. In terms of soil pH, all treatments exhibited a decrease of 0.02-0.68 units in the 0-20 cm soil layer compared with levels in 2006, while the 20-40 cm soil layer showed an increase of 0.20-0.48 units for all treatments except for $BF_1TD_1$, which had a lower value than the initial soil pH. The order of increase was $BF_1TD_1$ + OD > $BF_1TD_1$ + OS > $BF_2TD_1$ > $BF_1TD_2$.

After 11 years of the experiment, the 0-40 cm soil layer exhibited some alterations in SOM, AN, AP, AK, TN, TP, TK, and pH. Compared with the $BF_1TD_1$ treatment, the $BF_1TD_1$ + OD and $BF_1TD_1$ + OS treatments showed higher contents of SOM, AN, AP, AK, TN, and TP, with an average increase of 24.96 % and 39.68 % in SOM, and 52.25 % and 70.00 % in AN, respectively. AP increased by an average of 80.53 % and 132.48 %, while AK increased by 34.12 % and 35.84 %, respectively. The soil pH value of the $BF_1TD_1$ + OD treatment increased by 0.09 units compared with the $BF_1TD_1$ treatment, whereas the $BF_1TD_2$, $BF_2TD_1$, $BF_2TD_2$, $BF_1TD_1$ + OS treatments showed a decrease of 0.01-0.13 units.

## Discussion

A practical strategy for promoting sustainable agricultural development is the "4R" nutrient management, which includes "reasonable fertilizer location" to optimize nutrient application under suitable environmental conditions, enhancing nutrient uptake by crops, and reducing losses through fixation, volatilization, and leaching (Mi et al., 2018a). Improper fertilization placement can negatively affect the yield result in terms of wastage of fertilizer resources (Waqas et al., 2020). In this study, the average yield of maize kernels over the 12 years was basal fertilizer + topdressing deep application > basal fertilizer shallow application + topdressing deep application > basal fertilizer deep application + topdressing shallow application > basal fertilizer + topdressing shallow application. Although the impact of climatic changes varied, it revealed that deep chemical fertilizer applications generally outperformed shallow applications, and the combination of deep basal fertilizer and topdressing fertilizer applications had a positive effect on maize yield. Additionally, most above-ground nutrients such as nitrogen, phosphorus, and potassium were accumulated in the grains rather than stew. The base fertilizer + top fertilizer deep application had the best effect, followed by base fertilizer shallow application + top fertilizer deep application, followed by base fertilizer deep application + top fertilizer shallow application. This indicates that deep topdressing may enhance nutrient absorption and utilization (Sileshi et al., 2019). These findings are essential for guiding robotic precision fertilization in the black soil region of northeast China.

According to the analysis of long-term fertilization experiments in China (Zhang et al., 2019b), the average yield of corn increased by 2015 kg $ha^{-1}$ when chemical fertilizers were combined with organic fertilizers. In this research study, the fertilization method was optimized, and the maize grain yield under shallow and deep applications of organic fertilizer remained stable or showed a steady increase over the years of fertilization. In contrast, the maize yield under chemical fertilizer application alone was lower than that under the combined application of organic fertilizer and chemical fertilizer in the same year. The annual average yields of base fertilizer + topdressing + organic manure shallow application and base fertilizer + topdressing shallow application + organic manure deep application were 368.7 g per plant and 381.0 g per plant, respectively, which increased by 25.17 % and 29.34 % compared with the base fertilizer + topdressing shallow application. In 9 out of 12 years, deep application of organic manure led to higher yields than shallow application yielded. Deep application also resulted in increased biomass and accumulation of the nitrogen, phosphorus, and nutrients potassium in the grain. Growth increased by 4.39 %-8.08 %, 6.42 %-7.80 %, 4.84 %-5.91 %, and 1.38 %-15.50 %, respectively. Moreover, since 2012, the deep application of organic manure has shown a relatively stable increase in yield. These findings are consistent with Zhang et al. (2022) research and indicate that the 100-kernel weight influenced the increase in maize production. Deep application of organic manure boosted the increase of the 100-kernel weight of maize, which was 68.41 % greater than that in that shallow application. According to the DI, compared with the base fertilizer + topdressing shallow application, the yield and 100-kernel weight of the shallow and deep application of organic manure treatments increased, respectively, by 22.05 %, 27.46 %, 4.07 %, 6.81 % in the drought year, 36.18 %, 37.96 %, 7.11 %, 9.85 % in the normal-water year, and 15.19 %, 21.21 %, 3.60 %, and 7.01 % in the wet years. These findings suggest that the long-term application of deep organic manure cultivation could significantly improve maize production, ensure high yield stability, and eliminate the negative impact of inter-annual climate variations in maize yield.

The amount of organic matter in the soil is a crucial indicator of soil quality, and the presence of different nutrients in the soil greatly influences crop nutrient acquisition (Chai et al., 2019). As of 2016, each treatment made a sizable impact on environmental variables such as soil organic matter, available phosphorus, potassium, total nitrogen, total phosphorus, total potassium content, and soil pH. Compared with the baseline value from 2006, the soil organic matter content increased in each treatment with an average growth of 31.45 %. The effect of chemical fertilizer + organic manure deep application in the 20-40 cm was particularly notable, followed by chemical fertilizer + organic fertilizer shallow application, and then basal fertilizer + top dressing, which showed a slower increase. Additionally, compared with the levels in 2008, organic matter, alkali-hydrolyzed nitrogen, and total phosphorus in the 0-20 cm soil layer increased by 24.82 %, 28.95 %, and 53.06 %, respectively, and by 94.15 %, 171.67 %, and 202.63 % in the 20-40 cm soil layer after 10 years of deep application of organic manure. However, in the 0-20 cm soil layers, organic matter, total nitrogen, and total phosphorus increased by 19.89 %, 10.33 %, and 55.10 %, respectively, and in the 20-40 cm soil layer by 85.79 %, 135.24 %, and 127.50 %, respectively. Previous research has shown that extending the duration of organic fertilizer application greatly increases fertility variables such as soil organic carbon content, available nutrient supply, and enzyme activity in the topsoil, leading to a substantial increase in maize yield (Celestina et al., 2019). One of the key factors restricting the soil quality of arable land in Jilin Province is the rise in soil bulk density, particularly in the 20-40 cm soil layer, which poses a substantial barrier to deep plowing. The distribution of nutrients between the plow layer and the subsoil layer and deep fertilization can improve the soil fertility of the subsoil layer (Jankowski et al., 2018). The findings of this study further highlight that the deep application of organic manure is conducive to soil carbon sequestration and the rapid improvement of soil fertility, which is an essential technical approach to addressing the current issues of "shallow, thin, and nutrient-poor" arable land in black soil areas, achieving cultivation of the 0-40 cm full surface layer, and improving the quality of arable land.

Too low or too high soil pH will inhibit the activities of soil microorganisms and enzymes, while long-term single application of nitrogen fertilizer has been found to intensify soil acidification (Yang et al., 2019; Yu et al., 2019). Organic fertilizer input provides a carbon source for soil microbial activities and promotes soil-related enzyme activity (Zhang et al., 2019a; Yang et al., 2022). Conversely, a single application of chemical fertilizers can drastically lower soil pH (Liu et al., 2018). Applying organic fertilizer to inherently acidic soil can increase the negative charge and neutralize $H^+$ in the soil (Dai et al., 2019). In this study, regardless of the amount of rainfall, both shallow and deep applications of organic manure considerably increased the pH value of the soil in the 0-40 cm range. The soil pH value was 0.48 units higher than the baseline in 2006, indicating a substantial reduction in soil acidification. The comprehensive application of organic fertilizer can greatly improve soil fertility and buffering effectiveness.

In summary, our results suggest that long-term fertilizer treatments for topdressing and deep application are more advantageous than conventional application methods for improving maize productivity and nutrient absorption. Additionally, the average yield increased by 14.05 %, while the nutrient uptake of nitrogen, phosphorus, and potassium increased from 6.07 % to 22.17 %. After applying organic fertilizer, the average yield improved by 27.26 %. Nitrogen, phosphorus, and potassium uptake increased from 23.98 % to 54.87 %, while the average annual increase rates of organic matter and total nitrogen in the 20-40 cm soil layer were 7.33 % and 13.95 %, respectively. The soil pH tended to be appropriate, guaranteeing a stable, high maize yield. In Oct 2019, the State Council Information Office of the People's Republic of China issued a white paper entitled "Food Security in China" (SCIO, 2019), which highlighted a strategy for sustainable farmland use and the innovative application of agricultural technology to increase farmland productivity, and thus strengthen China's food security. Collectively, a comprehensive application of mechanical fertilizer combined with chemical fertilizer may maintain or even enhance maize production while increasing plant nutrient absorption, soil organic matter, nitrogen, phosphorous, and potassium supplies, and improve soil acidity. Considering all factors, applying base fertilizer at a depth of 15 cm, topdressing fertilizer at a depth of 10 cm, and organic fertilizer with the current deep tillage operation can help balance high maize production, nutrient uptake, and utilization, gradually improve soil fertility, and achieve high yield and efficiency through the integrated management of soil-crop intercropping systems to achieve sub-tillage fertilization.

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