

Erosion of topsoil decreases the yield and nutrient uptake of maize and soybean grown in Mollisols

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Abstract

We established three simulated erosion severities with topsoil depths of 10, 20 and 30 cm in a Mollisol farmland under a maize-soybean rotation system with no-tillage. After three consecutive years of field experiment, the decrease in topsoil thickness from 30 to 10 cm resulted in 9-22% of decrease in maize yield but not soybean. Compared to the 30 and 20-cm topsoil thickness, the 10-cm topsoil significantly lowered root and shoot biomass of maize at the jointing (V7) and milk stages (R3) and of soybean at the mid-seed filling stage (R6). Compared to the 30-cm topsoil, the 10-cm topsoil decreased available nitrogen and phosphorus in soil by 42% and 36% under maize, and by 25% and 19% under soybean, respectively, while the shallow topsoil also decreased N, P and K uptake per unit root length with the decreases being less for maize than soybean. Compared to the 30-cm topsoil, the 10-cm and 20-cm topsoil significantly increased the activities of urease, phosphatase and invertase in maize-grown soil, but not in soybean-grown soil except for the activity of urease in 10-cm topsoil. Maize was more sensitive to soil erosion than soybean due to the greater decreases in soil nutrient availability and its capability of nutrient uptake. The greater stimulation of nutrient mineralization processes in soil did not alleviate the nutrient constraint to maize yield under severe erosion conditions.

ABSTRACT

Soil erosion decreases topsoil depth, and hence soil fertility and crop productivity in agricultural systems. However, it is not clearly elucidated how different crop species adapt to the soil erosion regarding root function, nutrient uptake and rhizosphere biochemical properties, which is pivotal to cropping strategy under soil erosion. We established three simulated erosion severities with topsoil depths of 10, 20 and 30 cm in a Mollisol farmland under a maize-soybean rotation system with no-tillage. After three consecutive years of field experiment, the decrease in topsoil thickness from 30 to 10 cm resulted in 9-22% of decrease in maize yield but not soybean. Compared to the 30 and 20-cm topsoil thickness, the 10-cm topsoil significantly lowered root and shoot biomass of maize at the jointing (V7) and milk stages (R3) and of soybean at the mid-seed filling stage (R6). Compared to the 30-cm topsoil, the 10-cm topsoil decreased available nitrogen and phosphorus in soil by 42% and 36% under maize, and by 25% and 19% under soybean, respectively, while the shallow topsoil also decreased N, P and K uptake per unit root length with the decreases being less for maize than soybean. Compared to the 30-cm topsoil, the 10-cm and 20-cm topsoil significantly increased the activities of urease, phosphatase and invertase in maize-grown soil, but not in soybean-grown soil except for the activity of urease in 10-cm topsoil. Maize was more sensitive to soil erosion than soybean due to the greater decreases in soil nutrient availability and its capability of nutrient uptake. The greater stimulation of nutrient mineralization processes in soil did not alleviate the nutrient constraint to maize yield under severe erosion conditions.

Key words : soil erosion; topsoil depth; black soil; soil enzymes

Introduction

It is estimated that 15.1% of global land suffers degradation, of which 83.6% results from soil erosion (Lal, 2001; Gao et al., 2015). Soil erosion is a gradual process of removal, transport and deposition of topsoil caused by wind and water (Liu et al., 2010). The reduction of topsoil thickness is one of significant impacts of erosion on farmland. Topsoil thickness is a major indicator of soil quality and productivity (Sui et al., 2013). The reduction of topsoil thickness worsens soil physical, chemical and biological properties, and thus reduces crop productivity (Christensen and McElyea, 1988; Larney et al., 2000; Sarapatka et al., 2018). Therefore, preventing soil erosion and understanding the response of crop yields to the erosion is important in assessing the vulnerability of agriculture to erosion (Lal et al., 2000; Bakker et al., 2004).

It is difficult to establish the relationship of soil erosion and crop productivity as the process of degradation is slow (Bakker et al., 2004; Zhou et al., 2015). Previous studies have been conducted to assess the effects of soil erosion on crop productivity through artificial erosion approaches such as cut-and-fill experiments (Larney et al., 2000; Jagadamma et al., 2009), transects characterized by different erosion phases (Kosmas et al., 2001; Rejman and Iglík, 2010) and variable past erosions (Graveel et al., 2002; Fenton et al., 2005). Furthermore, simulation modeling has been established to estimate the long-term effect of soil erosion on plant growth (Pierce et al., 1983; Duan et al., 2016). For instance, Wang et al. (2009) demonstrated that soybean yield was exponentially decreased with increasing soil erosion depth due to the loss of soil organic matter and nutrients using the Agriculture Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model. However, these researches did not clarify the relationship of soil erosion and crop productivity, which may exhibit linear, concave and convex response curves (Bakker et al., 2004). Besides different experimental methods, the response of crop yield to soil erosion also depends on variables such as crop type, soil properties, management practices and climate characteristics (Bakker et al., 2007).

The negative effects of soil erosion on crop productivity can be attributed to the loss of soil organic carbon and plant nutrients, especially nitrogen (N), phosphorous (P), and potassium (K) (Kaspar et al., 2004; Herbrich et al., 2018). Quinton et al. (2010) reported that topsoil erosion decreased 23–42 Tg of nitrogen, 2.1–3.9 Tg of organic P and 12.5–22.5 Tg of inorganic P per year on the global scale. Plants obtain nutrients from soil mainly through roots; however, root growth in the soil vary with soil physical, chemical, and biological properties (Wang et al., 2015; Shinohara et al., 2016; Herbrich et al., 2018). It has been reported that a reduction of topsoil thickness caused by soil erosion results in decreases in soil organic matter (Liu et al., 2003; Srinivasan et al., 2012; Li et al., 2019a; Miao et al., 2019), available nutrients (Bakker et al., 2004; Sui et al., 2013; Xiong et al., 2018) and the effective rooting zone (Graveel et al., 2002). In addition, soil enzymes play an important role in soil quality and soil nutrient availability to plants (Jia et al., 2005; Stott et al., 2010; Sarapatka et al., 2018). Researchers have used soil enzyme activities as indicators of soil deterioration caused by erosion (Chaer et al., 2009; Sui et al., 2013; Nosrati, 2013). However, there are limited studies on nutrients uptake of crop and activities of enzymes as affected under zero tillage and residue cover in the eroded areas of China (Sui et al., 2013).

As an important grain production area, northeast China produces 18.7% of China's total grains of which 45% and 33% are soybean, and maize, respectively (National Bureau of Statistics of China, 2012). However, soil erosion increasingly becomes a major limiting factor for productivity of agricultural land in this region (Liu et al., 2010). Zhang et al. (2008) showed that the average thickness of topsoil layer decreased from 43.7 cm in 1982 to less than 30 cm in 2002. Sui et al. (2009) reported that the yield reduction in maize and soybean were 13% and 9% for the removal of every 10-cm topsoil. A survey with soil erosion in cropland in northeastern China over the past 300-year history conducted by Xie et al. (2019) showed that the soil loss of cropland exponentially increased due to the increasing cropland acreage in the steep slope areas.

In this study, we constructed three levels of topsoil depth in a Mollisol with the same physical, chemical and biological properties to explore how maize and soybean responded to topsoil erosion under zero tillage, residue cover and maize-soybean rotation conditions. The objectives were (1) to quantify the influence of

topsoil thickness on crop yield; (2) to compare nutrient uptake of crops under three topsoil depths; (3) to analyze the effect of topsoil thickness on root development and biochemical characteristics in the rhizosphere of the crop plants.

2. Materials and methods

2.1. Experimental design

A field experiment was established in 2015 in a farming field (47°53' N, 153deg33' E), Heilongjiang Province, northeast China. The soil was a typical Mollisol with glacial parent material. The field site had 40 years of cultivation history with a 5deg slope and 30 cm of A horizon. The annual average temperature in the region is 1.5degC, ranging from -37degC in the winter to 32degC in the summer. The average temperature is 18.1degC and rainfall during the growing season (from May to September) 424 mm.

The experiment deployed a split-block design with three simulated topsoil depths (10, 20 and 30 cm) as the main plot and crop species (maize and soybean) as sub-plot treatments. Each treatment had three replicates. Each plot had an area of 10.4 m x 7.5 m. We first removed all topsoil of experiment plots, mixed, and then back-filled up to 10, 20 and 30 cm in depth with a bulk density of 1.1 g cm⁻³. As the average depth of topsoil in the Mollisol region is 32.7 cm, this study treated the topsoil depth of 30 cm as the control, and 10-cm and 20-cm topsoil depths as erosion treatments. The reconstructed soil layer was naturally incubated for one year. Maize and soybean crops were grown in a rotation module, in which both maize and soybean were grown in the same season. Zero-tillage was deployed. The maize and soybean stalks were returned to the surface of field plots after harvesting.

Maize (*Zea mays* L. cv. Xinggen 5) and soybean (*Glycine max*(L.) Merr. cv. Dongsheng 1) were sown in early May 2016, 2017 and 2018. For maize, 150 kg ha⁻¹ of diammonium phosphate, 75 kg ha⁻¹ of urea, and 50 kg ha⁻¹ of potassium sulfate were applied before sowing, and 225 kg ha⁻¹ of urea was applied at the five-leaf collar (V5) stage. For soybean, the fertilizer application rates were 150 kg ha⁻¹, 50 kg ha⁻¹ and 50 kg ha⁻¹ for diammonium phosphate, urea and potassium sulfate, respectively. Sowing rates were 5 and 25 seeds m⁻² for maize and soybean, respectively. Maize plants were harvested at the jointing stage (V7) and milk stages (R3), and soybean plants were at the initial flowering (R1) and mid-seed-filling stage (R6).

2.2. Measurements

2.2.1. Biomass and seed yield

At each harvest, we randomly selected thirty plants of maize and soybean in each plot. The aboveground was cut and separated into leaves and stem. All plant samples were oven-dried at 105degC for 30 min and then 80degC for 72 h. In each plot, root samples were taken at three locations of each plot, i.e. top, middle and down sides of the plot with a root sampler (8 cm of diameter x 10 cm of depth) to sample roots up to 30 cm of soil depth at each location. The root samples were washed with tap water until free of soil, and were placed in a plexiglass tray with 4 mm of clean water in depth. Total root length, surface area and diameter were analyzed with the Win-RHIZO 2004 (Regent Instruments, Quebec, Canada) (Costa et al., 2002; Jin et al., 2012). After scanning, root samples were oven-dried to determine dry weight.

At the full maturity, two central rows of each plot were hand-harvested for yield estimation in 2016, 2017 and 2018. Grain yield was adjusted to 130 g kg⁻¹ moisture content.

2.2.2. Plants nutrient analysis

Plant samples were ground using a ball mill (Retsol MM2000, Retsch, Haan, Germany). Subsamples of shoots and roots were digested with a mixture of nitric and perchloric acid (4:1) (Jin et al., 2012). The concentrations of K in the digest solution was determined with a flame photometer (Liu et al., 2020). The P concentration were measured by SKALAR San⁺⁺ continuous flowing analyzer after acidic digestion (Xu et al., 2018). The concentrations of N in plant tissues were determined using an Elementar CNS analyser (Vario EL III, Elementar Analysensysteme GmbH, Germany) (Li et al., 2019b).

2.2.3. Available nutrients in the rhizosphere

The rhizosphere soils were collected by shaking the roots and the soil adhering to the roots was considered as rhizosphere soil (Nazih et al., 2001). All soil samples were stored in a refrigerator at 4 degC for further analysis.

Soil available N (NH_4^+ and NO_3^-) was determined with the methods described by Miah et al. (1998). Soil Olsen P was obtained by extraction in NaHCO_3 and analyzed by the Mo-Sb colorimetric method (UV2550, Shimadzu, Japan) (Bao, 2000). Available K was extracted with neutral 1 M NH_4OAc , and K concentration was measured by a flame photometer (Chen and Gabelman, 1995).

2.2.4. Enzyme activities in the rhizosphere

The activities of urease, phosphatase and invertase in rhizosphere soil were determined by indophenol colorimetric method, disodium phenyl phosphate and 3,5-dinitrosalicylic acid colorimetric methods, respectively (Ge et al., 2007).

2.3. Statistical analysis

Data were analysed with SPSS 13.0 software (Chicago, IL). Two-way ANOVA was used to determine the effects of topsoil depth, crop type and their interactions on seed yield, crop biomass, nutrient uptake, soil available nutrient and enzyme activity. Treatment means were compared using the Duncan's multiple range test ($P < 0.05$).

3. Result

3.1. Crop yield

Compared to the 30-cm topsoil depth, maize yield under the 10-cm topsoil depth decreased by 22%, 11% and 9% in 2016, 2017 and 2018, respectively ($P < 0.05$, Fig. 1a). Yield under the 20-cm topsoil depth significantly decreased only in 2016 ($P < 0.05$, Fig. 1a). Soybean yield did not decrease under the 10-cm topsoil depth, compared to the 30-cm topsoil depth. However, the 20-cm topsoil depth significantly increased yields in 2016 and 2018 ($P < 0.05$, Figs 1b & S1).

3.2. Root and shoot biomass

Root biomass of maize under the 10-cm topsoil was 35% and 10% lower at V7 and R3, respectively, compared to the 30-cm topsoil depth ($P < 0.05$, Fig. 2a). Similarly, shoot biomass also decreased with the decrease in topsoil depth except for 20-cm topsoil depth at R3 ($P < 0.05$).

In comparison, root biomass of soybean was significantly increased by 27% and 34% under the 20-cm topsoil depth at R1 and R6, respectively, than under the 30-cm topsoil depth. However, the 20-cm and 10-cm topsoil depths resulted in 27% and 36% of decrease in shoot biomass at R6, respectively, compared to 30 cm topsoil depth ($P < 0.05$, Fig. 2d).

3.3. Nutrient uptake

In maize, 10 cm of topsoil depth decreased shoot N, P and K uptake by 13%, 15% and 54% at V7, respectively, compared to 30 cm of topsoil depth. There was no difference in the N and K uptake between 30 cm and 20 cm of topsoil depths. An increase in N, P and K uptake was found under 20 cm of soil depth compared to 30 cm of soil depth at R3 ($P < 0.05$, Fig. 3).

In soybean, nutrient uptake did not decrease with decreasing topsoil depth at R1 except for shoot K uptake. However, at R6, N, P and K uptake significantly decreased under 20 cm and 10 cm of topsoil depth, compared to 30 cm of topsoil depth ($P < 0.05$, Fig. 3d, e, f).

Root had a similar trend in N, P and K uptake in response to different soil depths (Fig. S1).

3.4. Specific nutrient uptake rate

In maize, the N, P and K uptake per unit root length under 10 cm of topsoil depth significantly decreased by 44%, 46% and 57% at V7, respectively, compared to 30 cm of topsoil depths ($P < 0.05$, Fig. 4). There was no difference in the P and K uptake per unit root length between 30 cm and 20 cm of topsoil depths at V7. An increase in the N and K uptake per unit root length was found under 20 cm of topsoil depths compared to 30 cm of soil depth at R3.

In soybean, the N, P and K uptake per unit root length under 10 cm of topsoil depth was 46%, 42% and 50% lower than under 30 cm of topsoil depths at R1, respectively. The N, P and K uptake was 71%, 69% and 74% lower under 20 cm and 53%, 45% and 57% lower under 10 cm of topsoil depths than under 30 cm of topsoil depth at R6, respectively ($P < 0.05$, Fig. 4d, e, f).

The total root length in top 10-cm layer increased with decreasing topsoil depth for maize at V7 and soybean at R1. The total root length was maximum under 20-cm topsoil depth for maize at R3 and soybean at R6 (Fig. S2).

3.5. Available nutrients in the rhizosphere

The concentrations of available N and P in the rhizosphere of maize were 42% and 36% lower, respectively, under the 10-cm than the 30-cm topsoil depth ($P < 0.05$, Fig. 5a, b). Topsoil depth did not affect available K ($P > 0.05$, Fig. 5c). In comparison, the concentrations of available N, Olsen P and available K in the rhizosphere of soybean were 12%, 25% and 19% lower under the 10-cm than the 30-cm topsoil depth, respectively ($P < 0.05$, Fig. 5a, c). However, there was no difference in concentrations of available N, P and K between the 30-cm and 20-cm topsoil depths ($P > 0.05$, Fig. 5c).

3.6. Enzyme activities in rhizosphere

In the rhizosphere of maize, the activities of urease and phosphatase were 21% and 57% higher under 20 cm than 30 cm of topsoil depth. In addition, decreasing the topsoil depth to 10 cm further increased the activities of urease, phosphatase and invertase which were 22%, 162% and 14% higher compared to 30 cm of topsoil depths.

In soybean rhizosphere, urease activity was by 22% higher, but phosphatase activity 58% lower under the 10-cm than the 30-cm topsoil depth. The activities of phosphatases and invertase were 49% and 19% lower under 20 cm than 30 cm of topsoil depth, respectively ($P < 0.05$, Fig. 6c).

4. Discussion

Decreasing topsoil thickness decreased the seed yield of maize but not soybean. The great reduction of root and shoot biomass at V7 was associated with the maize yield reduction under shallow topsoil depths compared to thick topsoil (Fig. 2), because biomass production at this growth stage was essential to maize yield formation (Russo et al., 2004; Herrmann et al., 2013). Similarly, Lin et al. (2019) found that there was no difference in soybean yield between “light” and “moderate” erosion sites, but 11% of yield loss was observed in maize grown in the “moderate” erosion sites. These results demonstrated that the increasing soil erosion reduced crop productivity and the reduction magnitude might be dependent of crop species (Bakker et al., 2007; Gao et al., 2015; Lin et al., 2019).

The decreases in seed yield and biomass with the decrease of topsoil thickness might result from the reduction of nutrient supply in soil (Sanaullah et al., 2012; Bista et al., 2018). Our present study showed that 10 cm of topsoil depth decreased the N, P and K uptake per unit root length of both maize and soybean except maize at R3 (Fig. 4). As N, P and K are considered as the most important major nutrients for crop physiological function and production capacity (Wang et al., 2017), this study showed the linear correlations of total and specific nutrient uptake with total shoot biomass production (data not shown).

As soil nutrients are generally mainly distributed in the topsoil (Liu et al., 2013; Zhao et al., 2016), the decrease of topsoil thickness also decreased root nutrient acquisition. It was evident that nutrient uptake per unit root length of both crops was lower in 10 cm than 30 cm of topsoil depth at both vegetative and reproductive stages. Zobisch et al. (1995) reported that 3-6 t ha⁻¹ loss of topsoil resulted in 24% and 28%

of decreases in P and K uptake in maize, and 15% and 16% in beans. In addition, soil erosion reduced soil ammonium concentration by 66% at the Loess Plateau (Zheng et al., 2005), and soil organic C, total N and total P by 33%, 28% and 27%, respectively, at an alpine grassland (Nie et al., 2013). In this study, the decrease of the topsoil depth resulted in the substantial decreases in plant N and P uptake, and decreases in the available N and Olsen P concentrations in rhizosphere soil as well, but not much in available K. Our results indicated that the impact of the soil erosion on N and P cycles would constrain the crop productivity (Fig. 5). The stimulation of the urease, phosphatase and invertase activities in the rhizosphere of maize (Fig. 6) also indicated the scares of N and P availability to plants drove the biochemical processes of the N and P mineralization. In comparison, soybean yield did not respond to the decrease of topsoil thickness in this study. Similarly, Sui et al. (2009) found that soybean yield did not decrease by the removal of 5 cm topsoil, which had decreased maize yield by 10% in a black soil. It appeared that maize was more sensitive to topsoil erosion than soybean, which could be attributed to various capabilities of nutrient acquisition between crops. Nitrogen uptake per unit root length of maize was dramatically decreased at V7 than soybean at R1 under 10 cm of topsoil depth in comparison to 30 cm. This also implied that soybean plants were capable of fixing N_2 particularly when soil N fertility decreased due to the erosion/removal of fertile topsoil. In terms of P uptake, P availability under 10 cm of topsoil might not meet the nutrient demand of maize as low availability of P in the rhizosphere of maize and stronger phosphatase activity which can mineralize soil organic P for maize plants (Fig. 6). However, it did not occur in the rhizosphere of soybean. Some studies had found that soybean not only alleviated N deficiency due to N_2 -fixation (Li et al., 2017), but also had less P limitation than non-leguminous crops which had resulted from rhizosphere acidification during N_2 fixation to mobilize the non-labile P (Li et al., 2019b). Although low concentrations of available nutrients could stimulate enzymatic catalysis, mineralized nutrients might not sufficiently mitigate nutrient constraints to maize under erosion (Berhe et al., 2012). Since the quantity of enzymes is largely determined by microbial activity and the content of soil organic matter (Wang et al., 2012; Nie et al., 2015), further study is needed to understand how the soil microorganisms mineralize soil organic matter under topsoil erosion, considering C input and soil nutrient supply in the maize-soybean rotation system.

5. Conclusion Increasing topsoil erosion decreased yield of maize more severely than soybean. The deficiencies of N and P in maize under soil erosion might greatly constrain the productivity even though the nutrient mineralization was stimulated. Soybean was more resilient to topsoil erosion than maize. Increasing N and P supply would be applicable to alleviate yield loss of maize grown in eroded soils.

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Captions

Fig. 1. Effect of topsoil depth on grain yields of maize and soybean in 2016, 2017 and 2018. The main effects of topsoil depth, crop species and cropping year, and their interactions are all highly significant ($P < 0.001$). Values with means \pm standard error ($n=3$). Within a growing season of each panel, values with a same letter are not significantly different ($P > 0.05$).

Fig. 2. Effect of topsoil depth on root and shoot biomass of maize at the jointing (V7) and milk (R3) stages, and of soybean at the initial flowering (R1) and seed-filling (R6) stages in 2017. Values with means \pm standard error ($n=3$). Within a growth stage of each panel, values with a same letter are not significantly different ($P > 0.05$).

Fig. 3. Effect of topsoil depth on N, P and K uptake in shoot of maize at the jointing (V7) and milk (R3) stages, and of soybean at the initial flowering (R1) and seed-filling (R6) stages in 2017. Values with means \pm standard error ($n=3$). Within a growth stage of each panel, values with a same letter are not significantly different at ($P > 0.05$).

Fig. 4. Effect of topsoil depth on N, P and K uptake per unit root length of maize at the jointing (V7) and milk (R3) stages, and of soybean at the initial flowering (R1) and seed-filling (R6) stages in 2017. Values with means \pm standard error ($n=3$). Within a growth stage of each panel, values with a same letter are not

significantly different at ($P > 0.05$).

Fig. 5. Effect of topsoil depth on the concentrations of available N, P and K in the rhizosphere soil of maize at the milk stage (R3), and of soybean at the seed-filling stage (R6) in 2017. Values with means \pm standard error ($n=3$). Within each panel, values with a same letter are not significantly different at $P > 0.05$ among treatments in two crops (2-way ANOVA).

Fig. 6. Effect of topsoil depth on enzyme activities in the rhizosphere of maize at the milk stage (R3), and of soybean at the seed-filling stage (R6) in 2017. Values with means \pm standard error ($n=3$). Within each panel, values with a same letter are not significantly different at $P > 0.05$ among treatments in two crops (2-way ANOVA).

Table 1. Significant level (P) of main effects and interactions of topsoil depth and crop species on grain yield (2016, 2017, 2018), growth parameters (2017), nutrient uptake (2017), and concentrations of available nutrients (N, P and K) and activities of enzymes in the rhizosphere soil (2017) of maize at the jointing (V7) and milk (R3) stages, and of soybean at the initial flowering (R1) and seed-filling (R6) stages.

Fig. S1. Effect of topsoil depth on N, P and K uptake in root of maize at the jointing (V7) and milk (R3) stages, and of soybean at the initial flowering (R1) and seed-filling (R6) stages in 2017. Values with means \pm standard error ($n=3$). Within a growth stage of each panel, values with a same letter are not significantly different ($P > 0.05$).

Fig. S2. Effect of topsoil depth on total root length of maize at the jointing (V7) and milk (R3) stages, and of soybean at the initial flowering (R1) and seed-filling (R6) stages in the top 30 cm of soil profile in 2017. Values with means \pm standard error ($n=3$). Within a growth stage of each panel, values with a same letter are not significantly different ($P > 0.05$).

Table S1. The effect of topsoil depth on the concentrations of N, P and K in root, stem and leaves of maize at the jointing (V7) and milk (R3) stages, and of soybean at the initial flowering (R1) and seed-filling (R6) stages in 2017. Values with means \pm standard error ($n=3$). Values with a same letter are not significantly different between topsoil depths ($P > 0.05$).

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Table 1. Significant level (P) of main effects and interactions of topsoil depth and crop species on grain yield (2016, 2017, 2018), growth parameters (2017), nutrient uptake (2017), and concentrations of available nutrients (N, P and K) and activities of enzymes in the rhizosphere soil (2017) of maize at the jointing (V7) and milk (R3) stages, and of soybean at the initial flowering (R1) and seed-filling (R6) stages.

Year	Measurements	Growth stage	Topsoil depth	Crop species	Depth \times Species
2016	Grain yield	R3/R6	0.016	$P < 0.001$	0.012
2017	Grain yield	R3/R6	0.413	$P < 0.001$	0.597
2018	Grain yield	R3/R6	0.002	$P < 0.001$	0.634
2017	Shoot biomass	V7/R1	$P < 0.001$	$P < 0.001$	$P < 0.001$
		R3/R6	$P < 0.001$	$P < 0.001$	$P < 0.001$
	Root biomass	V7/R1	$P < 0.001$	$P < 0.001$	$P < 0.001$
		R3/R6	$P < 0.001$	$P < 0.001$	0.014
	Total root length	V7/R1	$P < 0.001$	$P < 0.001$	$P < 0.001$
		R3/R6	$P < 0.001$	$P < 0.001$	$P < 0.001$
	Root N uptake	V7/R1	$P < 0.001$	$P < 0.001$	$P < 0.001$
		R3/R6	0.001	$P < 0.001$	0.084
	Root P uptake	V7/R1	0.001	$P < 0.001$	$P < 0.001$
		R3/R6	0.369	$P < 0.001$	0.011
	Root K uptake	V7/R1	$P < 0.001$	$P < 0.001$	$P < 0.001$
		R3/R6	0.131	$P < 0.001$	0.461
	Shoot N uptake	V7/R1	$P < 0.001$	$P < 0.001$	$P < 0.001$
		R3/R6	0.001	$P < 0.001$	$P < 0.001$
	Shoot P uptake	V7/R1	0.007	0.001	0.213
		R3/R6	0.001	$P < 0.001$	$P < 0.001$
	Shoot K uptake	V7/R1	$P < 0.001$	$P < 0.001$	0.007
		R3/R6	$P < 0.001$	$P < 0.001$	$P < 0.001$
	Specific N uptake	V7/R1	$P < 0.001$	$P < 0.001$	0.003
		R3/R6	$P < 0.001$	$P < 0.001$	$P < 0.001$
	Specific P uptake	V7/R1	$P < 0.001$	$P < 0.001$	0.060
		R3/R6	$P < 0.001$	$P < 0.001$	$P < 0.001$
	Specific K uptake	V7/R1	$P < 0.001$	0.002	0.860
		R3/R6	$P < 0.001$	$P < 0.001$	$P < 0.001$
	Rhizosphere N	R3/R6	0.004	$P < 0.001$	0.027
	Rhizosphere P	R3/R6	0.002	0.001	0.797
	Rhizosphere K	R3/R6	$P < 0.001$	0.432	0.014
	Rhizo urease	R3/R6	0.006	$P < 0.001$	0.108
	Rhizo phosphatases	R3/R6	0.041	$P < 0.001$	$P < 0.001$
	Rhizo invertase	R3/R6	0.001	0.001	0.137

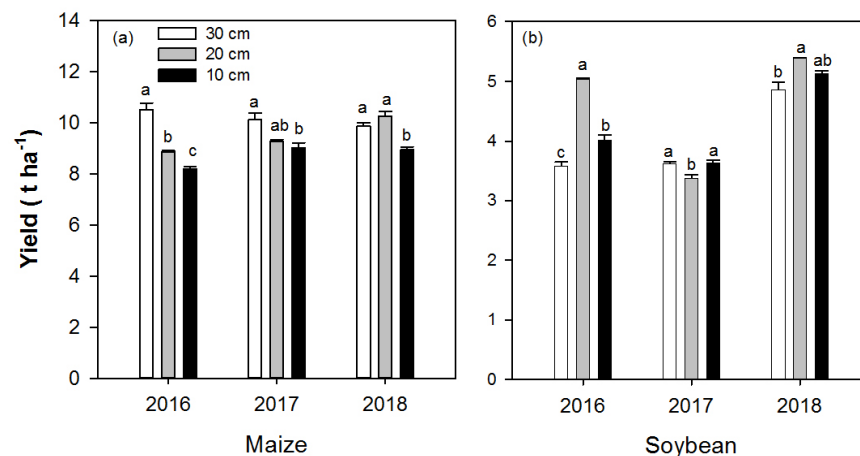


Fig. 1. Effect of topsoil depth on grain yields of maize and soybean in 2016, 2017 and 2018. The main effects of topsoil depth, crop species and cropping year, and their interactions are all highly significant ($P < 0.001$). Values with means \pm standard error ($n=3$). Within a growing season of each panel, values with a same letter are not significantly different ($P > 0.05$).

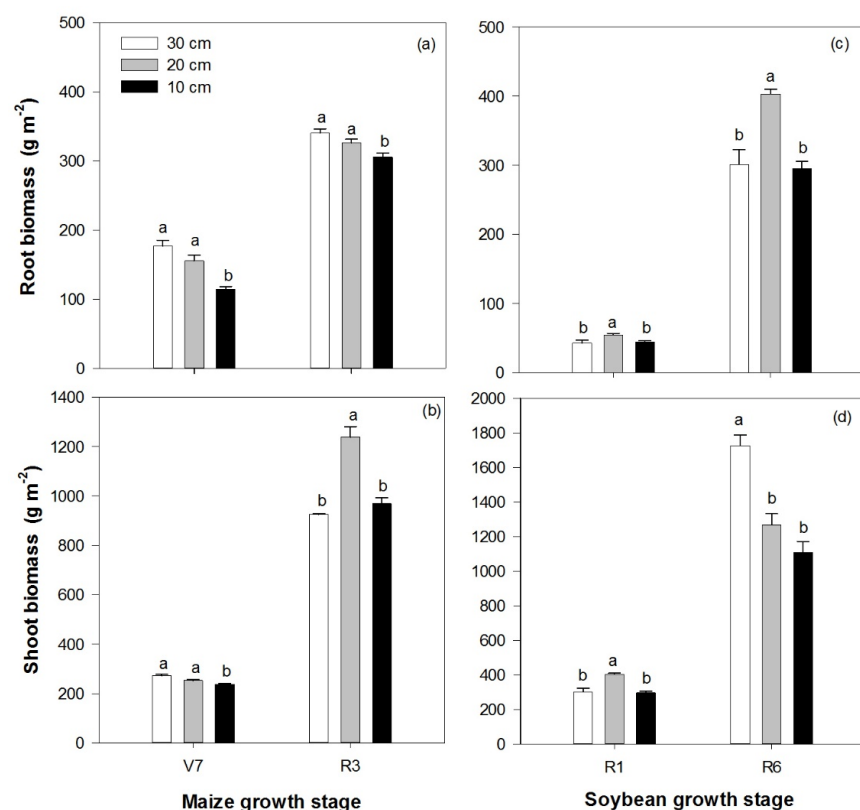


Fig. 2. Effect of reduced topsoil depth on root and shoot biomass of maize at the jointing (V7) and milk (R3) stages, and of soybean at the initial flowering (R1) and seed-filling (R6) stages in 2017. Values with means \pm standard error ($n=3$). Within a growth stage of each panel, values with a same letter are not significantly different ($P > 0.05$).

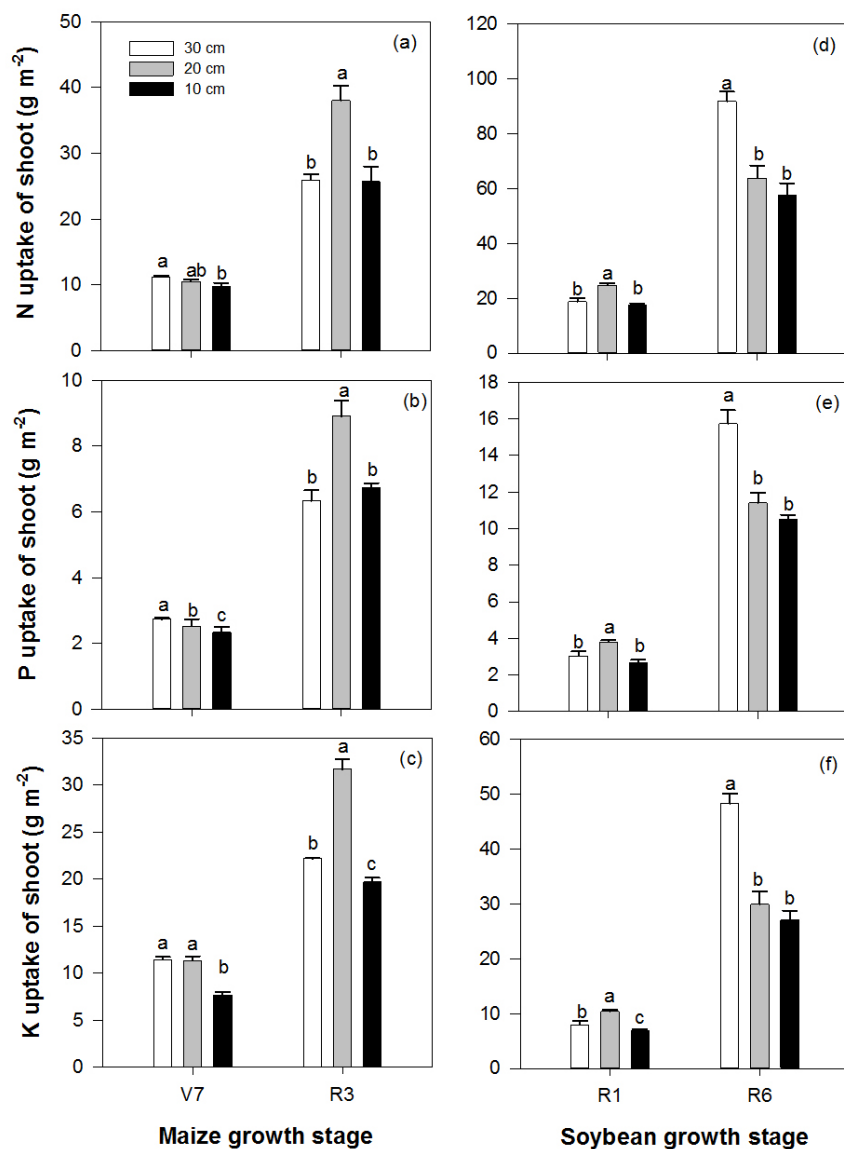


Fig. 3. Effect of topsoil depth on N, P and K uptake in shoot of maize at the jointing (V7) and milk (R3) stages, and of soybean at the initial flowering (R1) and seed-filling (R6) stages in 2017. Values with means \pm standard error (n=3). Within a growth stage of each panel, values with a same letter are not significantly different at ($P > 0.05$).

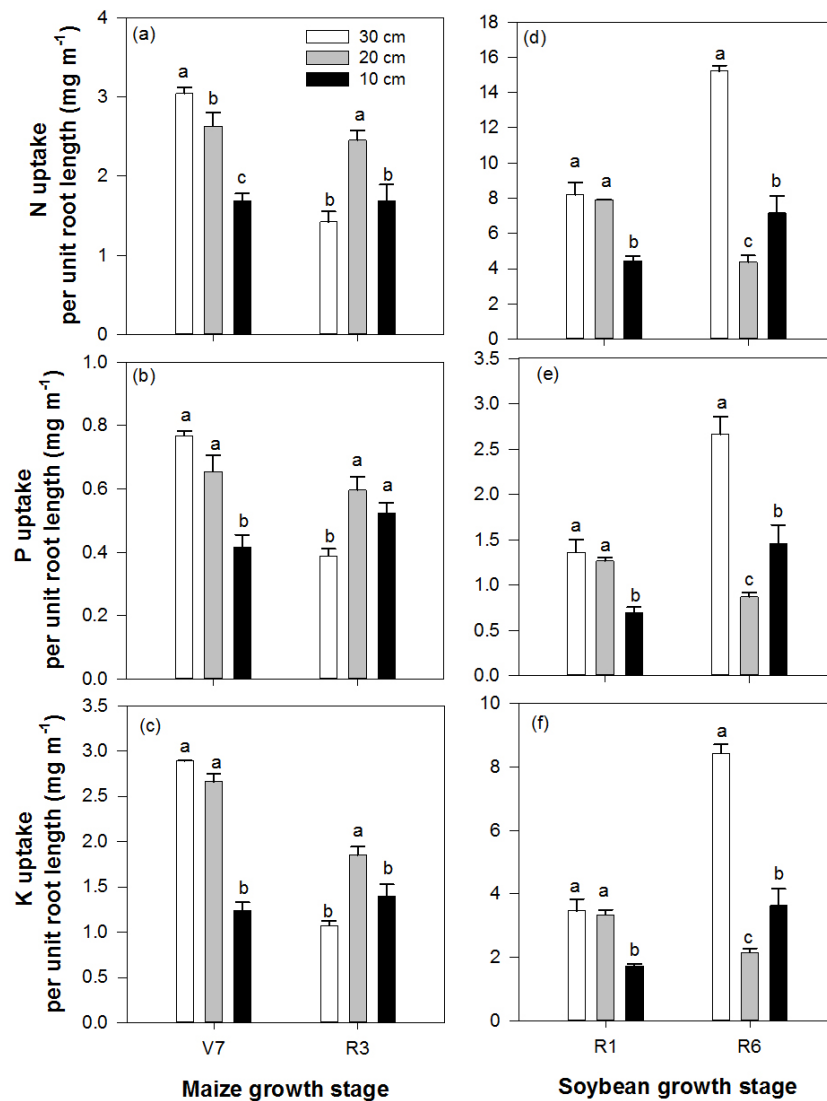


Fig. 4. Effect of topsoil depth on N, P and K uptake per unit root length of maize at the jointing (V7) and milk (R3) stages, and of soybean at the initial flowering (R1) and seed-filling (R6) stages in 2017. Values with means \pm standard error (n=3). Within a growth stage of each panel, values with a same letter are not significantly different at ($P > 0.05$).

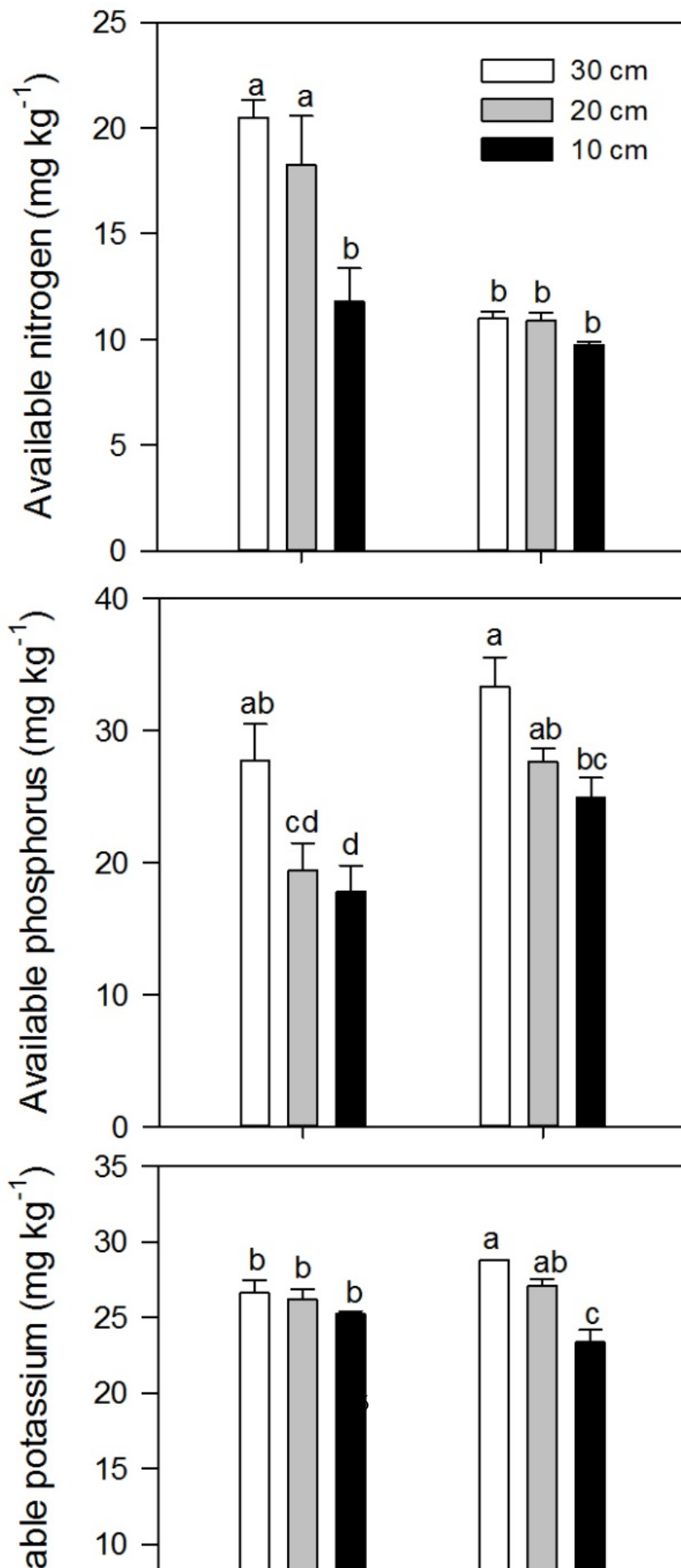


Fig. 5. Effect of topsoil depth on the concentrations of available N, P and K in the rhizosphere soil of maize at the milk stage (R3), and of soybean at the seed-filling stage (R6) in 2017. Values with means \pm standard error (n=3). Within each panel, values with a same letter are not significantly different at $P > 0.05$ among treatments in two crops (2-way ANOVA).

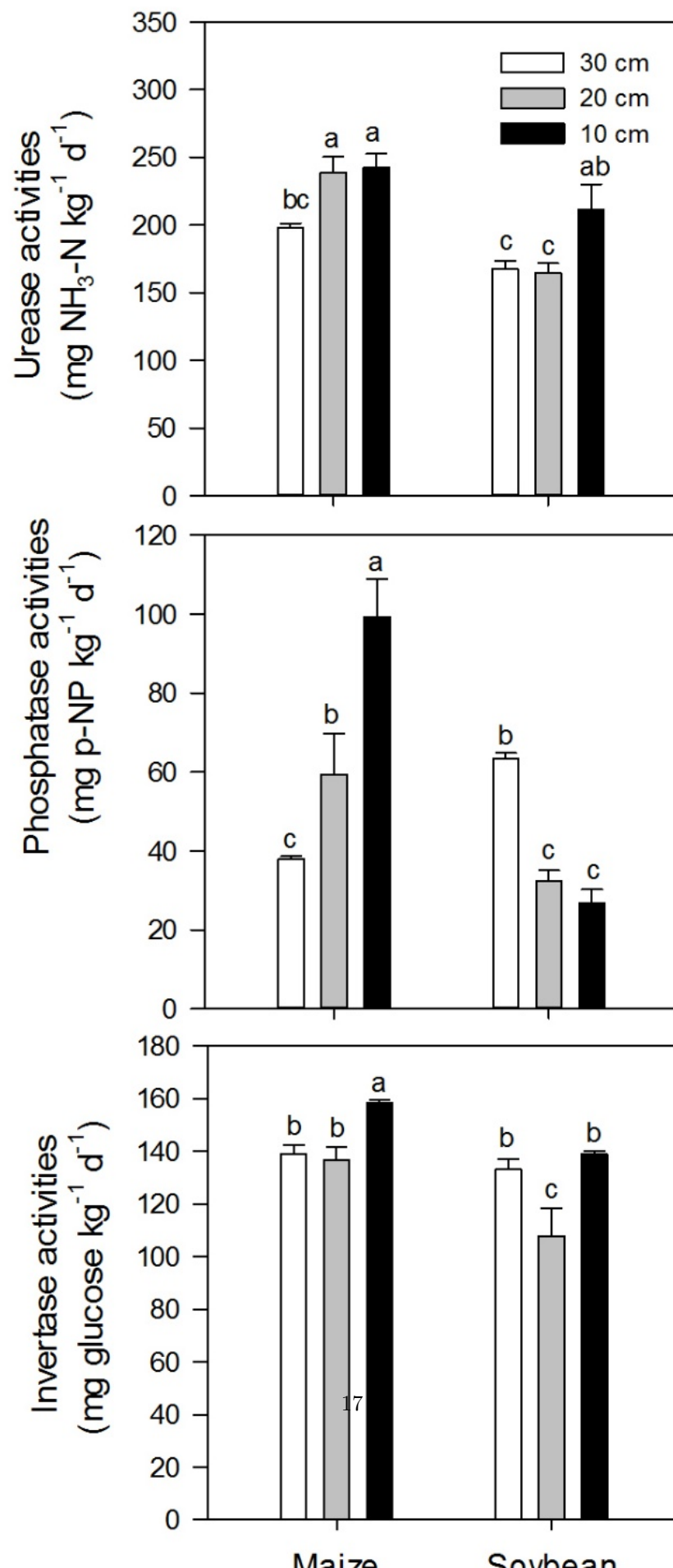


Fig. 6. Effect of topsoil depth on enzyme activities in the rhizosphere of maize at the milk stage (R3), and of soybean at the seed-filling stage (R6) in 2017. Values with means \pm standard error (n=3). Within each panel, values with a same letter are not significantly different at $P > 0.05$ among treatments in two crops (2-way ANOVA).

Table S1. The effect of topsoil depth on the concentrations of N, P and K in root, stem and leaves of maize at the jointing (V7) and milk (R3) stages, and of soybean at the initial flowering (R1) and seed-filling (R6) stages in 2017. Values with means \pm standard error (n=3). Values with a same letter are not significantly different between topsoil depths ($P > 0.05$).

Stage	Soil nutrients	Root (g kg ⁻¹)	Root (g kg ⁻¹)	Root (g kg ⁻¹)	Stem (g kg ⁻¹)	Stem (g kg ⁻¹)	Stem (g kg ⁻¹)
		10 cm	20 cm	30 cm	10 cm	20 cm	30 cm
2017 Maize	2017 Maize	2017 Maize	2017 Maize	2017 Maize	2017 Maize	2017 Maize	2017 Maize
V7	N	15.0 \pm 0.6a	13.3 \pm 0.7a	14.6 \pm 0.5a	16.1 \pm 1.5a	16.7 \pm 2.0a	16.4 \pm 0.8a
	P	4.2 \pm 0.1a	3.8 \pm 0.2a	4.2 \pm 0.1a	5.0 \pm 0.4a	5.2 \pm 0.4a	5.1 \pm 0.1a
	K	6.4 \pm 1.4a	8.8 \pm 0.4a	9.2 \pm 0.4a	17.7 \pm 3.8b	26.6 \pm 0.1a	24.2 \pm 0.4a
R3	N	6.4 \pm 0.6b	8.6 \pm 0.4a	7.7 \pm 0.7ab	5.8 \pm 0.5a	7.0 \pm 0.5a	6.6 \pm 0.9a
	P	3.5 \pm 0.3a	3.3 \pm 0.1a	3.6 \pm 0.2a	2.7 \pm 0.2a	2.8 \pm 0.1a	2.8 \pm 0.1a
	K	6.3 \pm 0.3a	6.8 \pm 0.7a	6.0 \pm 0.3a	10.9 \pm 1.4a	14.2 \pm 2.4a	12.5 \pm 1.2a
2017 Soybean	2017 Soybean	2017 Soybean	2017 Soybean	2017 Soybean	2017 Soybean	2017 Soybean	2017 Soybean
R1	N	14.4 \pm 0.2a	14.5 \pm 1.2a	14.9 \pm 0.6a	13.5 \pm 0.5a	15.8 \pm 2.2a	15.8 \pm 0.4a
	P	4.3 \pm 0.2a	4.8 \pm 0.1a	4.4 \pm 0.2a	3.8 \pm 0.1a	3.9 \pm 0.1a	4.1 \pm 0.1a
	K	3.6 \pm 0.4b	6.5 \pm 0.3a	5.9 \pm 0.6a	13.2 \pm 0.3a	14.0 \pm 0.7a	14.3 \pm 1.4a
R6	N	10.6 \pm 0.2a	11.5 \pm 0.9a	8.2 \pm 0.5b	13.6 \pm 0.9a	12.4 \pm 0.7a	13.1 \pm 0.1a
	P	4.4 \pm 0.4a	3.8 \pm 0.1a	2.7 \pm 0.2b	4.6 \pm 0.5a	4.1 \pm 0.2a	4.2 \pm 0.3a
	K	2.2 \pm 0.3b	2.9 \pm 0.3b	4.9 \pm 0.6a	8.6 \pm 0.1b	7.7 \pm 0.5b	10.8 \pm 0.4a

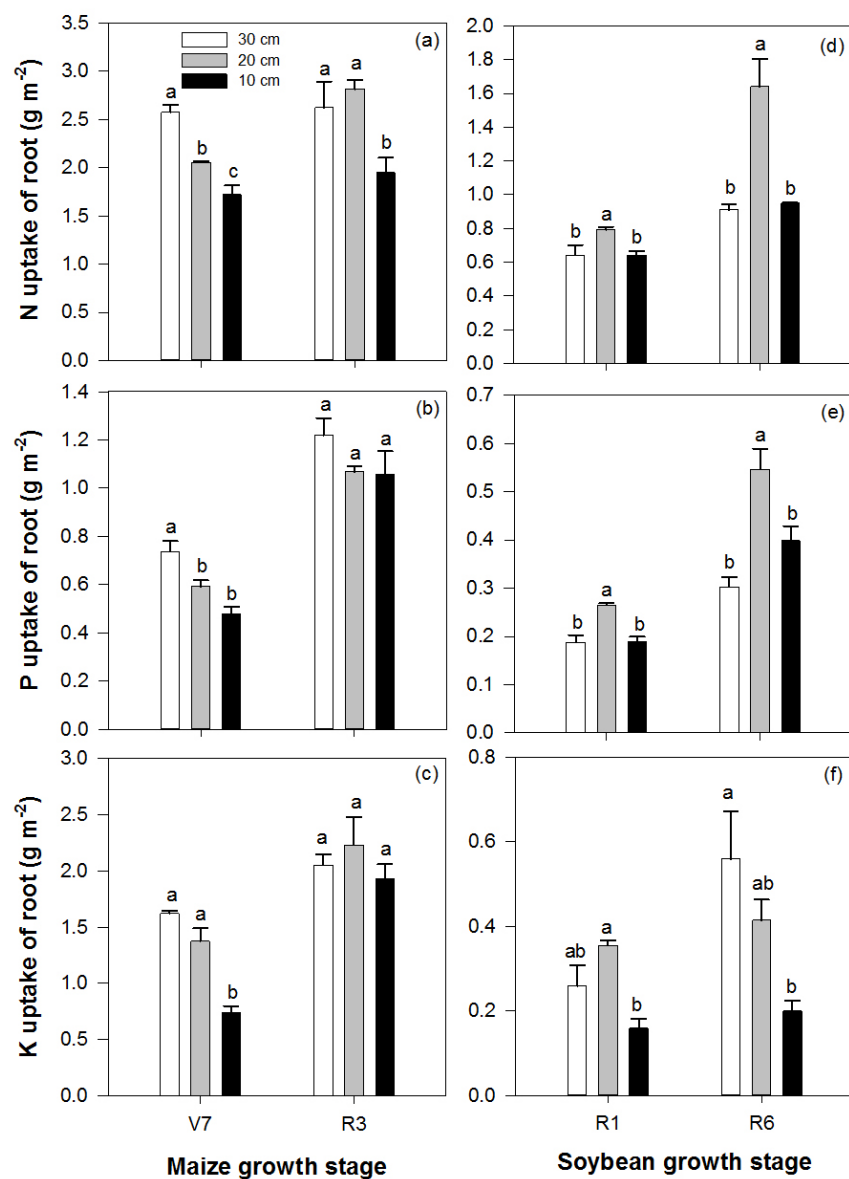


Fig. S1. Effect of topsoil depth on N, P and K uptake in root of maize at the jointing (V7) and milk (R3) stages, and of soybean at the initial flowering (R1) and seed-filling (R6) stages in 2017. Values with means \pm standard error (n=3). Within a growth stage of each panel, values with a same letter are not significantly different ($P > 0.05$).

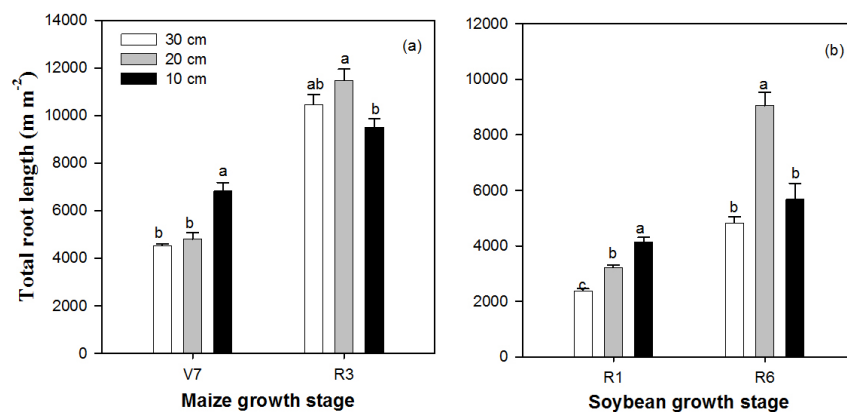
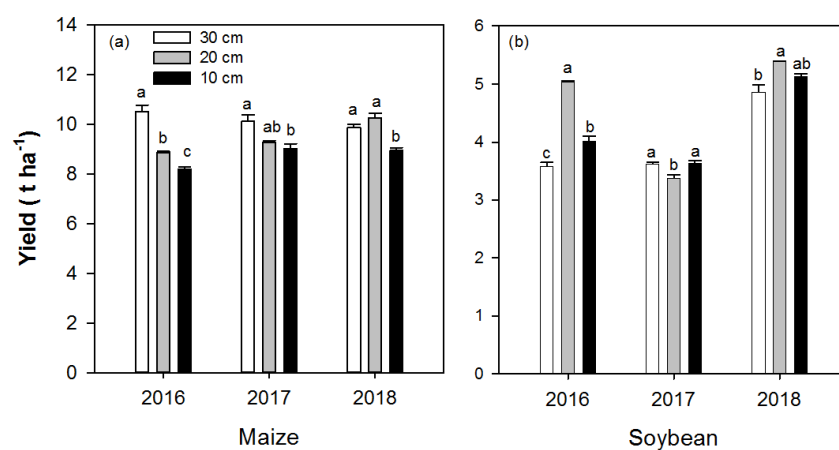
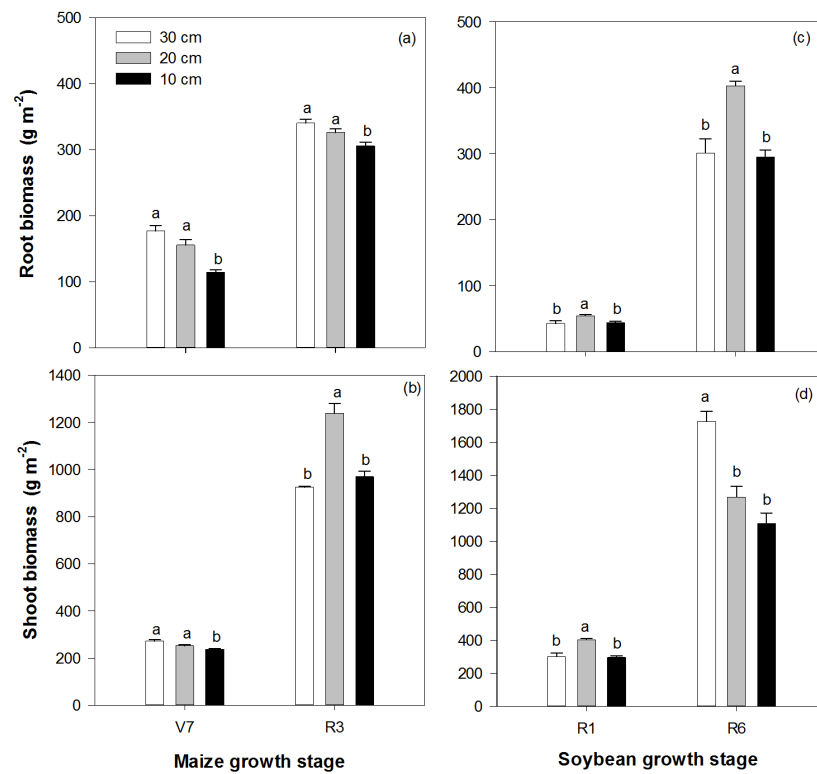
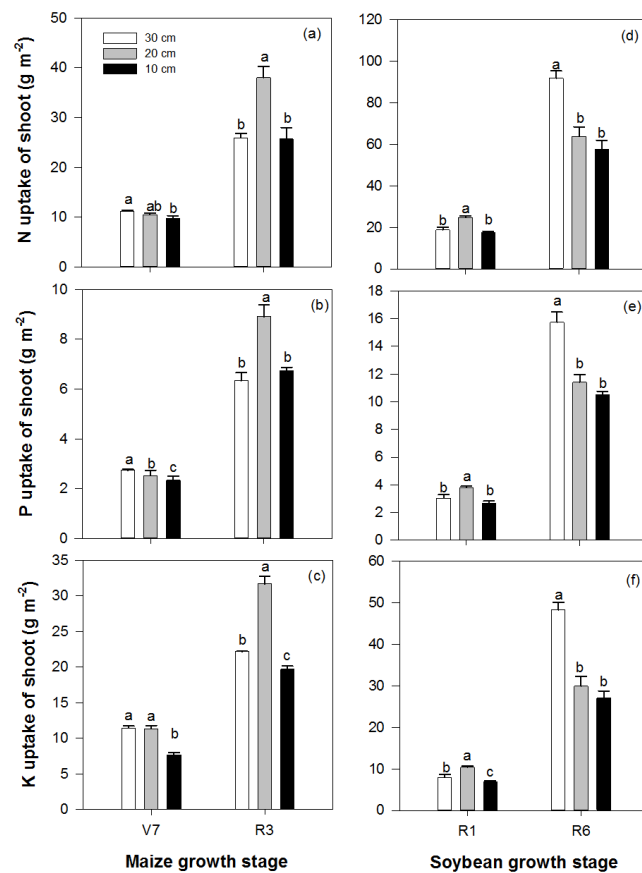
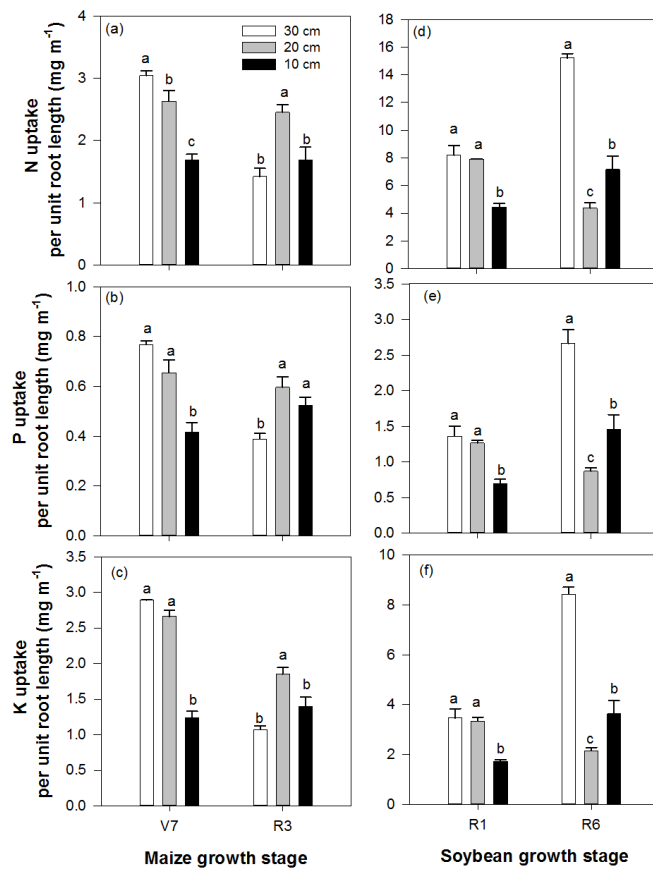


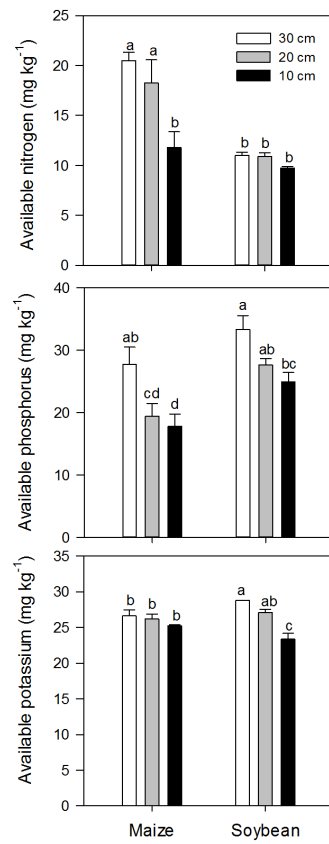
Fig. S2. Effect of topsoil depth on total root length of maize at the jointing (V7) and milk (R3) stages, and of soybean at the initial flowering (R1) and seed-filling (R6) stages in the top 30 cm of soil profile in 2017. Values with means \pm standard error (n=3). Within a growth stage of each panel, values with a same letter are not significantly different ($P > 0.05$).

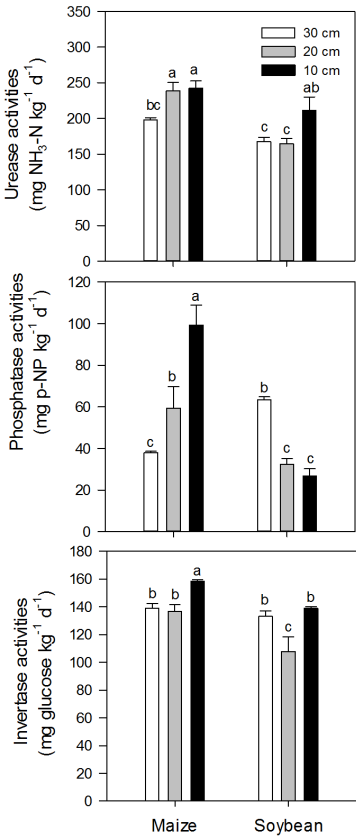












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