Soil & Tillage Research 212 (2021) 105024

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Variable tillage depth and chemical fertilization impact on irrigated common beans and soil physical properties

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ARTICLE INFO

Keywords:
Grain yield
Protein
Nitrogen
Phosphorus
Irrigation-use efficiency
Bulk density
Infiltration
Ukraine

ABSTRACT

Common bean (*Phaseolus vulgaris* L.) is an important grain crop in the world. Despite suitable soil-climatic conditions and high export potential, irrigated common bean production in Ukraine under performs due to a lack of sustainable management practices. The objective of our study was to evaluate the temporal effects of nitrogeN–Phosphorus (N–P) fertilization rates and tillage depth on the growth, yield, and water-use efficiency of common beans and selected soil physical properties. A 2 × 3 factorial experiment in a completely randomized design with four replications was conducted (2014–2016) at the Agricultural Land Cooperative Farm in the Kherson region of southern Ukraine. The factors were tillage depth (shallow tillage 0–20 cm vs. deep tillage of 0–30 cm) and N–P fertilization (control, $N_{45}P_{45}$, and $N_{90}P_{90}$ kg/ha). While tillage depth showed a marginal impact on the growth and yield of common beans, the N–P fertilization, in contrast, exerted significant effects on beans. Grain yields consistently increased by 25–30 % under $N_{45}P_{45}$ and $N_{90}P_{90}$ compared to the control; however, the effects of both $N_{45}P_{45}$ and $N_{90}P_{90}$ on grain yields were statistically similar. Likewise, the crude protein content was significantly higher by 17 % under $N_{90}P_{90}$ when compared to the control. As expected, the water-use efficiency (WUE) was significantly higher by 22–27 % under $N_{45}P_{45}$ and $N_{90}P_{90}$ when compared with the control; however, the $N_{45}P_{45}$ and $N_{90}P_{90}$ effects on WUE were non-significant. A similar effect (25–33 %) of N–P fertilizer was observed on irrigation-use efficiency (IUE) of beans. Soil bulk density (ρ_b) decreased significantly by 3 % in response to the temporal effects of the 0–30 cm tillage depth than that of the 0–20 cm tillage depth. Likewise, the 0–30 cm tillage depth significantly increased water infiltration by 7 % compared to the 0–20 cm tillage depth. The boundary line technique to evaluate the relationship between N–P fertilization and grain yield indicating that $N_{45}P_{45}$ produces near maximum economic grain production (95 %) comparable with $N_{90}P_{90}$, suggesting a savings of 45 kg/ha of both nitrogen (N) and phosphorus (P) fertilizers. While the impact of N–P fertilization was equally effective under both tillage depths, our results recommended that shallow tillage (0–20 cm) can be equally effective for irrigated common bean production to avoid deep tillage (0–30 cm).

1. Introduction

Common bean is one of the most important grain legumes (second only to soybeans) that are vital for global food security and the prevention of malnutrition (Reichert et al., 2015). Common bean comprises 50 % of the grain legumes consumed by humans worldwide (Bargaz et al., 2012; Abdi et al., 2014; Kouki et al., 2016). In addition to high digestive protein content, beans have high content of starch, alimentary fiber, and contain vitamins, minerals, bioactive compounds, carbohydrates, and small amounts of unsaturated lipids (Garden-Robinson and McNeal, 2013; Faria et al., 2014). It is estimated that a 100 g sample of bean contains 309 kcal (1293 kJ), which is twice that of beef and seven times higher than fish (Golovan, 2012). While common beans are capable of biological N-fixation to provide a substantial amount of their own N requirements, the post-harvest residues contain N-enriched compounds and subsequently improve N fertility for following crops (Chandra et al., 1987; Dhatonde and Nalamwar, 1996; Graham and Ranalli, 1997; Likhchvor, 2001; Hedge and Dwivedi, 1993;

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https://doi.org/10.1016/j.still.2021.105024
Received 17 October 2019; Received in revised form 28 February 2021; Accepted 13 March 2021
Available online 10 May 2021

Luchnaya and Petrenkova, 2009).

Despite high export potential and the suitable soil and climatic conditions for growing irrigated common bean in Ukraine, its steady peak production has not been achieved due to lack of sustainable management practices. Consequently, crop production has been seriously affected, and grain yield and quality have declined as a result of the impacts of imbalanced chemical fertilization, excessive plowing, and unregulated irrigation practices to achieve a high return on investment in Ukraine (Lykhovyd and Lavrenko, 2017; Ushkarenko et al., 2018). The most important soil and environmental factors that commonly affect bean production include N and P fertility, acidity or alkalinity, field workability by tillage, and high temperatures and drought (Amede et al., 2004; Bationo, 2004).

Nitrogen and P, as essential nutrients, play important roles in common bean growth and yield (Chandra et al., 1987; Dhatonde and Nalamwar, 1996; Kouki et al., 2016; Chekanai et al., 2018). Common beans reportedly have the lowest biological N-fixation rates among the most widely grown legumes in the world (Giller, 1990; Martinez-Romero, 2003; Furman and Dudchak, 2004; Gidago et al., 2011). Common bean N-fixation is generally considered lower than faba bean (*Vicia faba* L.), field peas (*Pisum sativum* L.), and lentils (*Lens culinary* Medic.). Generally, biological N-fixation alone may not provide enough N for a legume's demands throughout a growing season. During the early growth stages, beans cannot efficiently fix atmospheric N because they have very little or no rhizobia development. Supplemental N fertilization is expected to induce rhizobia proliferation and, subsequently, promote the establishment and growth of bean seedlings (Chandra et al., 1987; Chekanai et al., 2018). In contrast, higher rates of early N fertilization often promote excessive leaf growth to induce plant lodging, inhibit nodule formation, reduce biological N-fixation, and delay plant maturity (Burkanova, 2007).

Legumes, in general, require more P than non-legumes for root development and energy-driven processes like symbiotic N fixation (Anonymous, 1999). Biological N fixation in common bean, in particular, is more affected by P deficiency than in other legumes such as soybeans (Fageria and Baligar, 2016). Phosphorus availability in soils is particularly important for the nitrogenase enzyme to optimize nodulation for biological N-fixation. It is reported that about 40 % of crop production in the world's arable land is limited by P availability, and sub-optimal P fertilization often can result in 5–15 % yield losses annually (Bargaz et al., 2012; Kouki et al., 2016). Gidago et al. (2011) reported that 40 kg P/ha maximizes yield of haricot beans (*Phaseolus vulgaris* L.). In Ukraine, the chemical fertilization of common beans is performed using several different approaches including (i) the use of P-K fertilizers with supplemental N and biological inoculation; making PK+N_{10}-$_{30}$, PK+N_{30}-$_{60}$, and PK+N_{60}-$_{90}$, or (ii) a complete fertilization without taking N contribution from the biological N-fixation process (Dudchak, 2007).

Conventional tillage has long been a routine means of field preparation for growing agronomic crops in Ukraine (Kravchenko et al., 2012). Fall tillage is routinely used for growing common beans with deep tillage of 25–30 cm depth on loamy soils and up to 40 cm on heavy clay soils. One of the important aspects of expediency of plowing is to manage crop residues and improve field workability, increase uniform moisture distribution, and minimize irrigation requirements, increase nutrient availability for crops, and reduce pests and weed pressures (Doster et al., 1983; Ovcharuk, 2006; Schneider et al., 2017). Despite the potential benefits, the effects of repeated deep tillage operations, together with global climate change, are adversely affecting irrigated soil ecosystems by degrading soil structure, depleting soil organic matter (SOM), increasing soil erosion, and accelerating evaporation with increased irrigation requirements (Greenland, 1977; Islam and Weil 2000; Zvolinsky et al., 2011; Kravchenko et al., 2012; Burgos Hernández et al., 2019).

Rationalization of tillage practices to replace traditional deep tillage, at least by adapting shallow tillage toward conservation agriculture, is essential for economic crop production and reducing agroecosystem disservices. However, there is only limited information available on the integrated effects of N–P fertilization and tillage depth on common bean production under irrigated agriculture in Ukraine.

We hypothesized that temporal effects of variable tillage depths and N–P fertilizations will significantly affect common bean productivity and improve water infiltration by reducing compaction under irrigated agriculture. To test the hypothesis, the objective of our study was to evaluate the simple and interactive temporal effects of different N–P fertilization rates and tillage depths on the growth, yield, and irrigation-use efficiency of common beans, as well as water infiltration and soil compaction.

2. Materials and methods

2.1. Description of the site

A long-term field study was conducted (2014–2016) at the Agricultural Land Cooperative Farm in the Belozersky district (46°42′24.90″ N lat. and 32°16′27.77″ E long., 37 m above sea level) in the Kherson region of southern Ukraine. The climate is continental and semi-arid with moderately hot and dry seasonal cycles. The average frost period is about 233 days, and vegetative period is 188 days. Details of the climatic conditions are described in Table 1.

The soil is a dark Chestnut sandy clay loam (clay 30.1 %, silt 24.8 %, and sand 45.1 %) formed on the parent material consisting mainly of calcareous deposits with a predominance of loess-like loams, calcareous sandy loams, loess, calcareous sands, sandy loams, and alluvium. An initial analysis of the 0–30 cm range revealed a soil comprised of 1.45 % (humus 2.5 %) total organic carbon, 35 mg/kg of easily hydrolyzed nitrogen, 32 mg/kg of available phosphorus, 430 mg/kg of exchangeable potassium, and 0.1−2 meq/100 g of exchangeable Na, with a base saturation of 98 %, pH of 7, bulk density (ρ_b) of 1.35 g/cm^3, particle density (ρ_p) of 2.66 g/cm^3, total porosity at 49 %, field moisture capacity (θ_{FMC}) of 25.6 % at 0.03 MPa, permanent wilting point (θ_{PWP}) of 9.5 % at 1.5 MPa, and water infiltration of 1.3–2.2 mm/min. Groundwater depth was deeper than 5 m.

2.2. Experiment and cultural practices

A factorial experiment in a completely randomized design with four replications was established in March 2014. Each replicated plot was 216 m^2 (18 m long x 12 m wide) with a 2 m buffer between plots. The factors were tillage depth (0–20 cm vs. 0–30 cm) and chemical fertilization (0, $N_{45}P_{45}$, and $N_{90}P_{90}$ kg/ha).

After harvesting winter wheat, the field was tilled as per tillage depth treatments using a PLN-5−35 plow. Before planting, common bean seeds (Preto variety) were treated with commercially available mixed rhizobia strains (Rhizobophyte – bacterial strain Rhizobium I Bradyrhizobium; Biopolicide - spore bacteria Paenibacillus polymyxa; Phosphoenterin - bacterial strain Enterobacer nimipressuralis 32−3). Seeds were drilled at 6 cm depth with a driller SZ-5.4 at 400,000 seeds/ha. The plant row spacing was 45 cm. After planting, the herbicide Hezacyard 500 F W hp (Prometrin 500 g/l) was applied to the seedlings at 3 L/ha. At the beginning of the flowering stage, the insecticide Nurelle D (Hlorpirifos 500 g/l + Cipermetrin 50 g/l) was applied at 1 L/ha. Before harvesting, the bean was treated with non-selective contact desiccant Reglone Super 150 SL (active ingredient Diquat 150 g/l) at 2 L/ha.

2.3. Irrigation management and water quality

To determine irrigation scheduling and rates, the water balance method routinely followed in Ukraine was used (Kostyakov, 1960; FAO, 2020):

Table 1
Weather data during the crop growing season (2014 to 2016) in Kherson.

Month	Air temp. (^{0}C)			Rainfall (mm)			Rel. humidity (%)		
	2014	2015	2016	2014	2015	2016	2014	2015	2016
March	7.4	5.2	6.3	32	53.8	19.1	70	78	78
April	11.5	9.3	12.6	29.5	65.5	56.8	65	73	71
May	18	17	16.2	38.2	86.9	71.7	70	69	76
June	20.8	20.9	22.1	64.4	38.3	43	62	67	69
July	25.1	23.4	24.4	19.4	104.6	46.3	52	69	58
August	24.5	24.2	24.7	20.7	12.1	26.7	52	49	59
Total				204.2	361.2	263.3			
Average	17.9	16.7	17.7				61.8	67.5	68.5

Source: Kherson Agrometeorology Station, Ukraine.

$$I = 10 \times h \times \rho^b \times [(\theta_{FMC} - \theta_{ASM}),$$

Where, I is the irrigation rates (mm); 10 is a conversion factor; h is the effective root zone depth of the soil for field beans (cm); ρ^b is the soil bulk density (g/cm^3); θ_{FMC} is the FMC of soil at 0.03 MPa, and θ_{ASM} is the antecedent moisture content.

Ivanov equation (1954) was used to calculate for evaporation and other parameters to compensate irrigation scheduling at desired (75–80%) management allowable depletion (MAD) of soil moisture.

$$E = 0.0018 * (T + 25)2 * (100 – Rh)$$

where T is the air temperature and Rh is the relative humidity.

Based on the above calculations, three irrigations were applied to beans at 47.5 mm in 2014; two irrigations were applied at 50 mm in 2015; and three irrigations were applied at 45 mm in 2016. Any moisture losses associated with seepage, percolation, and capillary rise of water below 50 cm soil depth were considered negligible when the ground-water table is below 500 m depth under dry steppe climatic conditions in Ukraine.

Water used for irrigation was delivered from the nearby Ingulets irrigation system (47°00′49.41″ N lat. and 32°47′19.18″ E long. with a msl of 51.8 m), which is connected to the Ingul, Dnipro, and Ingulets rivers. The water contained total soluble salts 1.42 g/l, total Cl^- 8.57 meq/l, total alkalinity 3.73 meq/l, (Na + K) / (Ca + Mg + Na + K) 0.48, Mg/Ca 1.47, SAR 4.53, NH_4 0.07 mg/l, NO_3 1.27 mg/l, NO_2 0.04 mg/l, Fe 0.22 mg/l, Mn 0.052 mg/l, Cu 0.005 mg/l, Zn 0.026 mg/l, Ni 0.025 mg/l, detergents 0.048 mg/l, Cs_{37} 2.17 pKi, and Sr_{90} 6.9 pKi with a pH of 8.3.

2.4. Plant analysis

Plant height was determined at maximum vegetative growth on 20 randomly selected plants in each replicated plot. The leaf surface area was calculated by the method of Nichiporovich (1956), as follows:

$$S = \frac{ML \times A \times \pi D^2}{MC \times N \times 4 \times 10000}$$

where S is the leaf area of plant (m^2); ML is the mass of sample leaves (g); MC is the mass of leaf disc (g); D is the diameter of the leaf disc (cm); A is the number of leaf discs (pcs); N is the number of randomly selected plants (pcs); and π is the (22/7).

At harvest (~14 % grain moisture content), pod number/plant, bean/pod, 1000-seed weight, total grain yield, and grain N content of the beans were determined. Crude protein was calculated by multiplying the grain N content with a coefficient of 6.25.

2.5. Soil collection and analysis

Composite soils were collected at 0–30 cm depth from each replicated plot. Field-moist soils were air-dried under shade at room temperature (~ 25 °C) for a period of 15 days, ground with a rubber mallet followed by porcelain mortar and pestle, and 2-mm sieved prior to chemical and physical analysis.

Total soil organic C (TOC) was determined using the wet combustion method (Tyurin, 1937) based on C oxidation by 0.4 N $K_2Cr_2O_7$ in acid solution (1:1 H_2SO_4- H_2O):

$$3C(SOM) + 2K_2Cr_2O_7 + 8H_2SO_4 \rightarrow 2Cr_2(SO_4)_3 + 2K_2SO_4 + 8H_2O + 3CO_2$$

The TOC content determined by the wet combustion method, multiplied by a factor of 1.724 to obtain humus (SOM) contents. The alkaline hydrolysed nitrogen (Roberts et al., 2011) and available phosphorus (SSTU-4114−2002) were determined by standard methods of analysis. Exchangeable Ca, Mg, K, and Na, and base saturation were determined by following the standard methods of SSTU 4114, 2002.

The ρ_p and ρ_b were calculated using standard pycnometer and core methods, respectively. Using the standard pressure plate apparatus procedure, the FMC and PWP of soil were determined to be 0.033 and 1.5 Mpa, respectively (Klute, 1986). Water infiltration was determined by following the double-ring infiltration method (ASTM, 2003) using two cylindrical rings (with diameters of 30 and 20 cm) placed on the clean soil surface (without crop residues, living plants, and cracks or holes) in each plot. Water infiltration was performed five times in each replicated plot. The calculation of water infiltration rates of the soil (Inf) for individual periods of time was performed according to the formula:

$$Inf = \frac{TW}{S \times t}$$

where, Inf is the water infiltration rates of soil (mm/min); S is the area of the inner cylindrical ring (cm^2); TW is the total volume of water used (cm^3); and t is the time interval (min.).

2.6. Water analysis

Irrigated water quality was assessed as per agronomic and environmental criteria in accordance with the standard methods (Likhovid, 2015) followed by the Mykolaiv Regional Department of Water Resources, Ukraine. The sodium adsorption ratio (SAR) was calculated by Ayers and Westcot (1985):

$$SAR = \frac{Na}{\sqrt{\frac{Ca+Mg}{2}}}$$

where SAR is the sodium adsorption ratio (meq/L) and the Na, Ca, and Mg are the extracted ion concentrations (meq/L).

Water toxicity by eCl was calculated (SSTU 2730, 2015) as follows:

$$eCl = Cl^- + 0.2SO_4^{2-} + 0.4HCO_3^- + 10CO_3^{2-},$$

where Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-} are the extracted ion concentrations (meq/L).

Sodium percentage (SP) was calculated by using the formula (Todd, 1980):

$$SP = \left(\frac{Na}{Na + K + Ca + Mg}\right) \times 100\%$$

where SP is the exchangeable sodium percentage (%) and the Na, K, Mg, and Ca are the extracted ion concentrations (meq/L).

2.7. Water and irrigation-use efficiency

Total water available as consumptive water use (CWU) for growing common beans was determined using the water balance method (Kostyakov, 1960; Anonymous, 1997) as described below:

$$CWU = I + R + (\theta_i - \theta_f)$$

where CWU is the total volume of water available provided to the beans during the growing season (mm); I is the total depth of irrigation (mm) to the effective root zone of beans (50 cm) during the growing season; R is the total rainfall (mm) during the bean-growing season; θ_i is the moisture content at 0–100 cm soil depth at the beginning of the beaN–Planting season (mm); and θ_f is the residual moisture content at 0–100 cm soil depth at the end of the bean-growing season (mm), taking into account the evapotranspiration, seepage loss, and capillary rise of water.

The 100 cm depth was taken into consideration for measuring soil moisture because of the depth (0 to +98 cm) of the soil profile with calcareous/gypsic materials and the effective root zone (50 cm) of the field beans for irrigation.

Water-use efficiency (WUE) was calculated as the ratio of the bean grain yield divided by the total volume of water available and/or provided for growing beans. Likewise, irrigation-use efficiency (IUE) was determined as the ratio of the bean grain yield divided by the total volume of irrigation (I) applied over the growing period.

$$WUE\ (kg/mm) = [bean\ grain\ yield\ (kg/ha)]\ /\ E\ (mm/ha)$$

$$IUE\ (kg/mm) = [bean\ grain\ yield\ (kg/ha)]\ /\ I\ (mm/ha)$$

2.8. Optimization of chemical fertilization and crop yield

Common bean grain yield (averaged across years) under two different tillage depths was regressed with N–P levels using the boundary line technique to calculate for optimum P fertilization to achieve at least 95 % of the common bean yield (Webb, 1972).

2.9. Statistical analysis

Significant differences in the crop growth and yield attributes, as well as soil parameters attributed to the impact of tillage depth and N–P fertilization rates, were evaluated by a two-way analysis of variance procedure of the SAS (SAS Institute, 2008). Both tillage depth and N–P fertilization rates were considered as fixed effects. Simple and interactive effects of treatment combinations were separated by the Least Significant Difference (LSD) test with a value of $p \leq 0.05$ unless otherwise mentioned. Regression and correlation analyses were performed by SigmaPlot®.

3. Results and discussion

3.1. Growth and yield attributes of common beans

While the tillage depth did not exert any significant effects, N–P fertilization, in contrast, in different ways affected common bean growth and yield attributes over time (2014–2016) without any interactions with tillage depth (Tables 2,3, and 4). In 2014, plant height and leaf area of common beans were significantly higher by 8% and 12 %, respectively, for $N_{45}P_{45}$; and 18 % and 22 %, respectively, for $N_{90}P_{90}$ when compared to the control (Table 2). Plant height and leaf area were 9% and 8%, respectively, higher in the $N_{90}P_{90}$ than in the $N_{45}P_{45}$. Bean pods per plant and 1000-seed weight increased significantly by 17 % and 6 %, respectively, when $N_{90}P_{90}$ was applied relative to the control. The harvested bean yield was consistently higher by 23 % under $N_{45}P_{45}$ and 31 % under $N_{90}P_{90}$ compared to the control. When $N_{90}P_{90}$ was applied, the crude protein content of beans increased by 17 % over that of the control; however, the grain yield and protein contents were statistically similar under both $N_{45}P_{90}$ and $N_{90}P_{90}$ treatments.

During the 2015 growing season, plant height and leaf area were consistently increased by N–P fertilization when compared to the control. The pod numbers per plant increased by 9–31 % under N–P fertilization when compared to the control; however, the pod numbers did not vary significantly between $N_{45}P_{45}$ and $N_{90}P_{90}$ treatments (Table 3). Likewise, the 1000-seed weight and crude protein contents significantly increased by 4% and 12 %, respectively, under $N_{90}P_{90}$ compared to those of the control. While bean yields consistently increased in response to N–P fertilization by 22–26 % when compared with the control, the yield did not differ significantly between $N_{45}P_{45}$ and $N_{90}P_{90}$ treatments. Like 2014 and 2015 growing years, the effects of chemical fertilization were consistently positive on bean growth and yield attributes in 2016 (Table 4).

Results showed a significant temporal variation on common bean growth except for leaf area, yield, and crude protein contents (Table 5).

Table 2
Tillage depth and nitrogen-phosphorus fertilization effects on common bean growth and yield attributes (2014 data presented).

Depth (cm)	Fertilization (kg/ha)	Plant ht. (cm)	LA (cm^2)	Pod/ plant	1000-seed wt. (g)	Yield (Mg/ha)	Protein (%)	WUE (kg/mm)	IUE
0–20		50.2a[¥]	41.9a	13a	115.8a	2.29a	20.5a	0.72a	1.58a
0–30		51.3a	43.1a	13a	115.7a	2.34a	20.7a	0.69a	1.61a
	Control	46.7x[≠]	38.1x	12x	112.3x	1.96x	18.9x	0.61x	1.35x
	$N_{45}P_{45}$	50.5y	42.9y	13xy	116.1xy	2.41y	20.7xy	0.73xy	1.66y
	$N_{90}P_{90}$	55z	46.6z	14y	118.9y	2.57y	22.2y	0.77y	1.77y
Tillage x Fertilization									
0–20	Control	46.3ns	37.5ns	12ns	112.6ns	1.94ns	18.8ns	0.62ns	1.4ns
	$N_{45}P_{45}$	49.9	42.4	13	116.4	2.39	20.6	0.75	1.6.5
	$N_{90}P_{90}$	54.5	45.9	14	118.4	2.54	22.1	0.78	1.7.5
0–30	Control	47.2	38.6	12	112.1	1.98	19	0.6	1.3.6
	$N_{45}P_{45}$	51	43.4	13	115.8	2.44	20.8	0.72	1.6.8
	$N_{90}P_{90}$	55.6	47.2	14	119.3	2.6	22.3	0.76	1.7.9

LA = Leaf area, WUE = Water-use efficiency, and IUE = Irrigation-use efficiency.

[¥] Mean values in each column separated by same lower case (a and b) were not significantly different by tillage depth at $p \leq 0.05$.

[≠] Mean values in each column separated by same lower case (x, y, and z) were not significantly different by N–P fertilization rates at $p \leq 0.05$.

Table 3
Tillage depth and nitrogen-phosphorus fertilization effects on common bean growth and yield attributes (2015 data presented).

Depth (cm)	Fertilization (kg/ha)	Plant ht. (cm)	LA (cm^2)	Pod/ plant	1000-seed wt. (g)	Yield (Mg/ha)	Protein (%)	WUE (kg/mm)	IUE
0–20		55.8a[¥]	41.5a	15a	122.6a	2.41a	20.4a	0.71a	2.41a
0–30		57.5a	43a	15a	124.8a	2.46a	20.6a	0.7a	2.46a
	Control	52.3x[≠]	39.7x	13x	121.4x	2.10x	19.3x	0.62x	2.1x
	$N_{45}P_{45}$	57y	42.2xy	16y	123.7xy	2.56y	20.6xy	0.74xy	2.56y
	$N_{90}P_{90}$	60.6z	44.8y	17y	126.1y	2.65y	21.6y	0.76y	2.65y
Tillage x Fertilization									
0–20	Control	51.6ns	39.1ns	13ns	120.5ns	2.08ns	19.2ns	0.63ns	2.1ns
	$N_{45}P_{45}$	56.3	41.3	16	122.4	2.53	20.5	0.75	2.53
	$N_{90}P_{90}$	59.4	44	17	125	2.62	21.5	0.77	2.62
0–30	Control	53	40.4	13	122.3	2.12	19.4	0.62	2.12
	$N_{45}P_{45}$	57.6	43.1	16	124.9	2.59	20.7	0.73	2.59
	$N_{90}P_{90}$	61.7	45.6	17	127.3	2.67	21.7	0.75	2.67

LA = Leaf area, WUE = Water-use efficiency, and IUE = Irrigation-use efficiency.
[¥] Mean values in each column separated by same lower case (a and b) were not significantly different by tillage depth at $p \leq 0.05$.
[≠] Mean values in each column separated by same lower case (x, y, and z) were not significantly different by N–P fertilization rates at $p \leq 0.05$.

Table 4
Tillage depth and nitrogen-phosphorus fertilization effects on common bean growth and yield attributes (2016 data presented).

Depth (cm)	Fertilization (kg/ha)	Plant ht. (cm)	LA (cm^2)	Pod/ plant	1000-seed wt. (g)	Yield (Mg/ha)	Protein (%)	WUE (kg/mm)	IUE
0–20		51.6a[¥]	40.5a	12a	116.3a	2.28a	21a	0.65a	1.69a
0–30		52.8a	41.5a	12a	117.8a	2.33a	21.2a	0.65a	1.73a
	Control	47.4x[≠]	36.8x	11x	114.5x	1.87x	18.9x	0.54x	1.39x
	$N_{45}P_{45}$	51.8y	41.4y	13y	117xy	2.45y	21.4xy	0.69x	1.81y
	$N_{90}P_{90}$	57.2z	44.8z	13y	119.7y	2.61y	23y	0.72x	1.93y
Tillage x Fertilization									
0–20	Control	47ns	36.5ns	11ns	113.8ns	1.84ns	18.8ns	0.54ns	1.37ns
	$N_{45}P_{45}$	51.2	40.9	13	116.1	2.42	21.3	0.68	1.79
	$N_{90}P_{90}$	56.5	44.2	13	119.1	2.58	22.9	0.72	1.92
0–30	Control	47.9	37.2	11	115.3	1.9	19	0.54	1.41
	$N_{45}P_{45}$	52.5	41.9	13	117.9	2.47	21.4	0.69	1.83
	$N_{90}P_{90}$	58	45.3	13	120.3	2.63	23.1	0.71	1.95

LA = Leaf area, WUE = Water-use efficiency, and IUE = Irrigation-use efficiency.
[¥] Mean values in each column separated by same lower case (a and b) were not significantly different by tillage depth at $p \leq 0.05$.
[≠] Mean values in each column separated by same lower case (x, y, and z) were not significantly different by N–P fertilization rates at $p \leq 0.05$.

A higher growth and yield response, especially plant height, pod number per plant, and 1000-seed weight of beans, was observed in 2015 when compared to the 2014 and 2016 growing seasons. Averaged across years (2014–2016), while tillage depth showed a marginal impact on the growth and yield of common beans (Table 5), the N–P fertilization, in contrast, exerted significantly consistent effects on beans. Plant height increased by 9–18 % and leaf area increased by 10–19 % under $N_{45}P_{45}$ and $N_{45}P_{45}$ when compared to the control. The pod number per plant and 1000-seed weight increased under $N_{90}P_{90}$ by 25 % and 5 %, respectively, relative to the control. Grain yields consistently increased by 25–30 % under $N_{45}P_{45}$ and $N_{90}P_{90}$ compared to the control; however, the effects of both $N_{45}P_{45}$ and $N_{90}P_{90}$ on grain yields were statistically similar. Likewise, the crude protein content was significantly higher by 17 % under $N_{90}P_{90}$ when compared to the control.

A significant increase in growth and yield of common beans through the effects of N–P fertilization was expected, as previous reports have shown that yield, pods per plant, seeds per pod, and 1000-seed weight were significantly affected by N, P, and K fertilizations (Da Silva et al., 1993; Zhao et al., 1993; Arf et al., 2011; Argaw and Akuma, 2015; Yin et al., 2018). Several studies have reported that greater leaf area, pods per plant, seeds per pod, and higher 1000-grain weight are all indices of high grain components of beans (Zhao et al., 1993; Cheng and Tian, 2011; Rahimi et al., 2012). Edje et al. (1975) reported that seed yield increased with the addition of 40 kg N/ha (2.7 ton/ha) compared to the non-fertilized control (2.1-ton/ha). However, N rates from 40 to 160 kg N/ha produced statistically similar grain yields, and the yield was only significantly higher at the 200 kg N/ha (3.8-ton/ha) when compared to the 40 kg N ha^{-1} rates (Buetow et al., 2017). While Eckert et al. (2011) reported that increasing N level did not influence seed yield or seed weight of beans, Chidi et al. (2002), in contrast, reported that common bean response to N fertilization varied more with cultivars and environmental factors than with the fertilizations.

Similar to N, P fertilization increased pods per plant and 1000-seed weight, and improved common bean productivity due to increased nodular numbers, shoot dry-matter, pod numbers, and other yield attributes of common beans (Bargaz et al., 2012; Abdi et al., 2014; Turuko and Mohammed, 2014; Hmissi et al., 2015; Fageria and Baligar, 2016). It is reported that improving P nutrition to legumes, especially in P-deficient soils, generally (i) increased P acquisition (root morphology, root exudation, and P uptake mechanisms) and (ii) enhanced P utilization by internal mechanisms associated with the efficient use of absorbed P at the cellular level (Raghothama, 1999; Vance, 2001; Bargaz et al., 2012). This finding was also observed in our study, where the bean yield increased with P fertilization.

A lack of consistent difference in bean yields observed by variable tillage depths was unexpected (Tables 2–5). While the placement and distribution of available nutrients in close proximity to the plant roots is an important factor in increasing crop yields, a mixing of N and P within large volumes of soil using 0–30 cm tillage depth (compared to 0–20 cm) was expected to be more conducive to growing roots and their access to N, P, and other nutrients. It is assumed that a lack of consistently higher bean yields with deep tillage (compared to shallow tillage)

Table 5
Tillage depth and chemical fertilization effects on common bean growth and yield attributes over time (2014, 2015 and 2016 data presented).

Year	Depth (cm)	Fertilization (kg/ha)	Plant ht. (cm)	LA (cm^2)	Pod/plant	1000-seed wt. (g)	Yield (Mg/ha)	Protein (%)	WUE (kg/mm)	IUE
2014			50.7a[¥]	42.5a	13a	115.8a	2. 31a	20.6a	0.71a	1.6a
2015			56.6b	42.2a	15b	123.7b	2.44a	20.5a	0.71a	2.44b
2016			52.2a	41a	12a	117.1a	2.31a	21.1a	0.65a	1.71a
	0–20		52.5x[≠]	41.3x	13x	118.3x	2.33x	20.6x	0.69x	1.89x
	0–30		53.8x	42.5x	13x	119.4x	2.38x	20.8x	0.68x	1.93x
		Control	48.8A[£]	38.2A	12A	116.1A	1.98A	19A	0.59A	1.61A
		$N_{45}P_{45}$	53.1B	42.2B	14AB	118.9A	2.47B	20.9AB	0.72B	2.01B
		$N_{90}P_{90}$	57.6C	45.4C	15B	121.6B	2.61B	22.3B	0.75B	2.12B
Year x tillage depth x fertilization										
2014	0–20	Control	46.3	37.5	12	112.6	1.94	18.8	0.62	1.34
		$N_{45}P_{45}$	49.9	42.4	13	116.4	2.39	20.6	0.75	1.65
		$N_{90}P_{90}$	54.5	45.9	14	118.4	2.54	22.1	0.78	1.75
	0–30	Control	47.2	38.6	12	112.1	1.98	19	0.6	1.36
		$N_{45}P_{45}$	51	43.4	13	115.8	2.44	20.8	0.72	1.68
		$N_{90}P_{90}$	55.6	47.2	14	119.3	2.6	22.3	0.76	1.79
2015	0–20	Control	51.6	39.1	13	120.5	2.08	19.2	0.63	2.08
		$N_{45}P_{45}$	56.3	41.3	16	122.4	2.53	20.5	0.75	2.53
		$N_{90}P_{90}$	59.4	44	17	125	2.62	21.5	0.77	2.62
	0–30	Control	53	40.4	13	122.3	2.12	19.4	0.62	2.12
		$N_{45}P_{45}$	57.6	43.1	16	124.9	2.59	20.7	0.73	2.59
		$N_{90}P_{90}$	61.7	45.6	17	127.3	2.67	21.7	0.75	2.67
2016	0–20	Control	47	36.5	11	113.8	1.84	18.8	0.54	1.37
		$N_{45}P_{45}$	51.2	40.9	13	116.1	2.42	21.3	0.68	1.79
		$N_{90}P_{90}$	56.5	44.2	13	119.1	2.58	22.9	0.72	1.92
	0–30	Control	47.9	37.2	11	115.3	1.9	19	0.54	1.41
		$N_{45}P_{45}$	52.5	41.9	13	117.9	2.47	21.4	0.69	1.83
		$N_{90}P_{90}$	58	45.3	13	120.3	2.63	23.1	0.71	1.95
$LSD_{p<0.05}$										
Year*Tillage depth			ns	ns	ns	2.23	ns	ns	ns	ns
Year*Fertilization			ns	ns	ns	ns	ns	0.2	ns	ns

LA = Leaf area, WUE = Water-use efficiency, and IUE = Irrigation-use efficiency.

[¥] Mean values in each column separated by same lower case (a and b) were not significantly different by time (year) at $p \leq 0.05$.

[≠] Mean values in each column separated by same lower case (x, y, and z) were not significantly different by tillage depth at $p \leq 0.05$.

[£] Mean values in each column separated by same upper case (x, y, and z) were not significantly diff.

was associated with the mixing of a large volume of deeper, but nutrient-poor soil (<20 cm) and nutrient dilution and availability, especially P, to the growing beans. The soil depth at which 50 % of total root mass was accumulated for different crops varied from 8 cm to 20 cm (Fan et al., 2016), which justified our results.

3.2. Water and irrigation-use efficiency of common beans

The water-use efficiency (WUE) of common beans was consistently influenced by N–P fertilization; however, the tillage depth did not exert any significant effects or interactions with N–P fertilization (Tables 2–4). During the 2014 growing season, the WUE of beans was significantly higher (26 %) under $N_{90}P_{90}$ than under the control. Likewise, the irrigation-use efficiency (IUE) was significantly higher by 23 % and 31 % under $N_{45}P_{45}$ and $N_{90}P_{90}$, respectively, when compared to the control. The effects of $N_{45}P_{45}$ and $N_{90}P_{90}$ on the IUE of beans did not vary significantly.

As expected, the WUE of beans varied significantly by N–P fertilization in 2015. When $N_{90}P_{90}$ was applied, the WUE increased by 23 % compared to the control. In contrast, N–P fertilization consistently increased the IUE of beans by 22–26 % compared to the control; however, the effects of variable N–P fertilization rates on IUE were statistically similar. Unlike 2014 and 2015, the WUE of beans did not vary significantly by N–P fertilization in 2016; however, the IUE of beans did vary significantly by 30–39 %. While the WUE did not vary significantly among the years, the IUE did vary significantly. The highest IUE was measured in 2015 (27–53%) compared to both the 2014 and 2016 growing seasons.

When combined over time and fertilization, neither the WUE nor IUE varied significantly in response to the effects of variable tillage depths. As expected, both WUE and IUE were affected by the impact of N–P fertilization. The WUE was significantly higher by 22–27 % under $N_{45}P_{45}$ and $N_{90}P_{90}$ when compared with the control; however, the effects of N–P fertilization were statistically similar between the $N_{45}P_{45}$ and $N_{90}P_{90}$ rates. A similar effect (25–33 %) of N–P fertilization was observed on the IUE of beans. While the time x depth had a significant effect on 1000-seed weight, the time x N–P fertilization affected crude protein content of beans, without any other interactions (Table 5).

3.3. Soil physical properties

Tillage depth and N–P fertilization variably influenced the ρb without any significant interactions (Fig. 1). While the tillage depth at 0–30 cm decreased ρb by more than 2 %, the 0–20 cm tilling depth decreased only 1 % from their initial ρb values. The ρb decreased significantly by 3 % in response to the temporal effects of the 0 to 30 cm tillage depth than that of the 0–20 cm tillage depth. In contrast, N–P fertilization did not cause any significant differences in ρb values. Water infiltration characteristics of soil were variably affected by tillage depth and N–P fertilization without any interactions (Fig. 2). The 0–30 cm tillage depth significantly increased water infiltration rates by 7 % relative to the 0–20 cm tillage depth. Moreover, the temporal effects of both tillage depths significantly increased (9–16 %) water infiltration compared to that of their initial water infiltration rates. In contrast, N–P fertilization did not exert any significant effects on the water infiltration characteristics of the soil.

The ρ_b decreased significantly after three years of 0–30 cm depth tillage operations in response to the effects of repeated cutting, turning, crumbling, and mixing of the greater volumes of soil than that of the 0–20 cm depth tillage (Fig. 1). Our results were similar with the

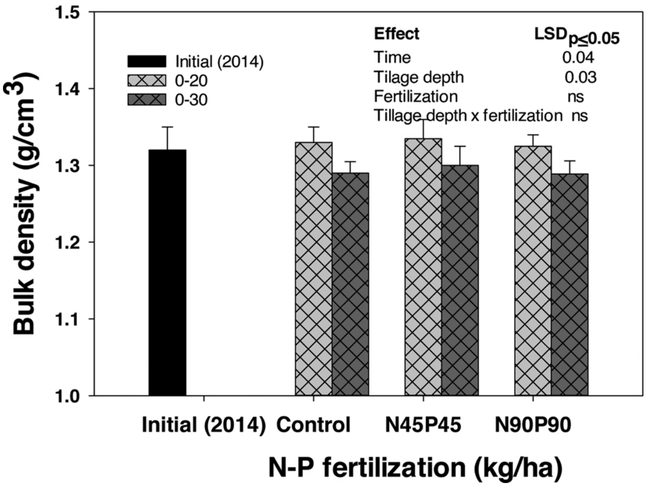

Fig. 1. Effects of tillage depth and nitrogen-phosphorus fertilization on soil bulk density (averaged across 2014, 2015, and 2016 data). Error bar indicates standard error of means.

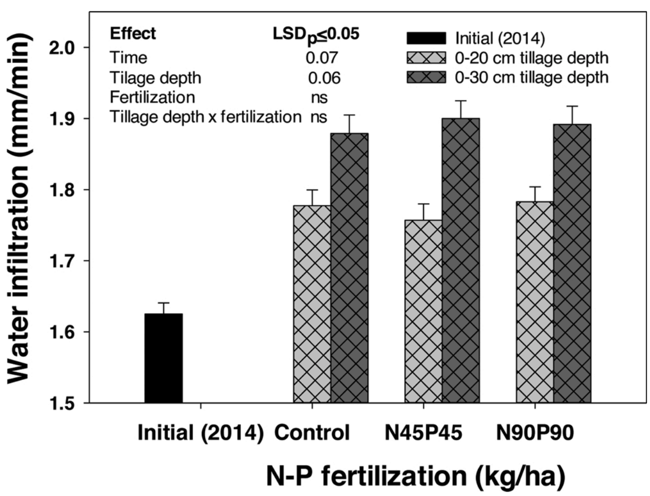

Fig. 2. Effects of tillage depth and nitrogen-phosphorus fertilization on steady-state water infiltration rates of soil (averaged across 2014, 2015, and 2016 data). Error bar indicates standard error of means.

previous studies that reported higher ρb values (by 10–12 %) in shallow-tilled soil, compared to reduced ρb in deep-tilled soil (Håkansson and Medvedev, 1995; Lowery and Schuler, 1991; Feiza et al., 2008).

Water infiltration of soil was significantly higher with deeper tillage (0–30 cm) compared to shallow tillage (0–20 cm), which was probably due to reduced soil compaction (decreased ρb) and increased porosity (Croissant et al., 1991).

3.4. Optimization of N–P fertilization and tillage depth for common beans

When the bean grain yield was plotted over N–P fertilization rates, a significant nonlinear response ($y = 2.08 + 0.014X – 0.00087X^2$ with an adjusted $R^2 = 0.986$ for 0−20 cm tillage depth and $y = 2.12 + 0.015X – 0.00097X^2$ with an adjusted $R^2 = 0.981$ for 0−30 cm tillage depth) was observed over tillage depth (Fig. 3). Results showed that N–P fertilization increased the grain yield under both tillage depths; however, the grain yield did not vary significantly at high rates of N–P fertilization ($N_{45}P_{45}$ vs. $N_{90}P_{90}$). Several studies reported that higher rates of P fertilization are often associated with increased N uptake, or vice-versa, by plants due to maintaining a balance in N:P stoichiometry (Ma et al., 2016; Tao et al., 2016). This is most important in determining the

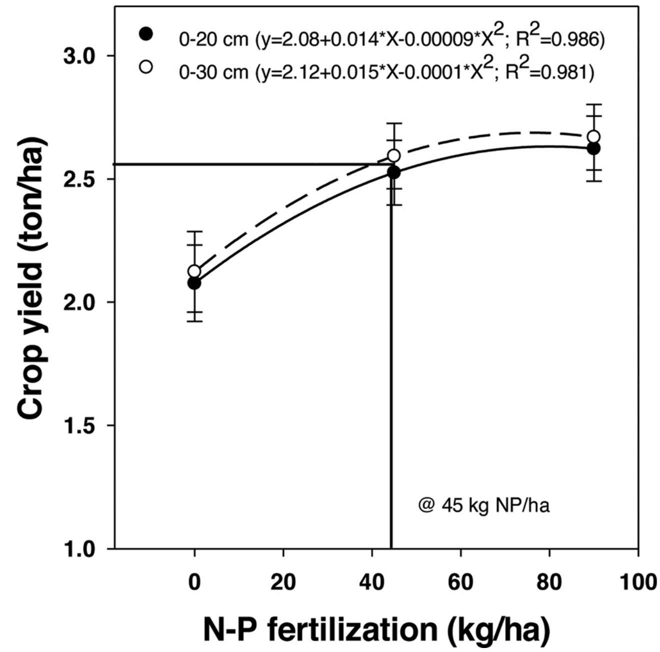

Fig. 3. Boundary line technique to determine the optimal rates of N-P fertilization for common bean production at different tillage depths (averaged across 2014, 2015 and 2016 data). Error bar indicates standard error of means.

economic rates of N–P fertilization for common beans. Based on the boundary line technique, the fertilization vs. crop yield relationship suggested that $N_{45}P_{45}$ produces near maximum grain production (95 %), comparable with the $N_{90}P_{90}$, suggesting a savings of 45 kg/ha of both N and P fertilizers to support sustainable irrigated common bean production.

While the impact of N–P fertilization was equally effective under both tillage depths, our results suggested that the shallow tillage (0–20 cm) was optimum for common bean production under irrigated conditions rather than the traditionally used deep tillage (0–30 cm).

4. Conclusions

Averaged across three-year studies (2014–2016), the common bean yield attributes did consistently increase under both $N_{45}P_{45}$ and $N_{90}P_{90}$ compared to the control; however, their effects were statistically similar. As expected, both WUE (22–27%) and IUE (25–33%) of beans improved under the impact of N–P fertilization. In contrast, the temporal effects of tillage depth did not significantly affect soil properties, except water infiltration rates. The boundary line technique suggested that $N_{45}P_{45}$ supported near maximum grain production (95 %) comparable with the $N_{90}P_{90}$, suggesting a savings of 45 kg/ha of each of N and P fertilizers. Moreover, our results recommended that shallow tillage (0–20 cm) can be routinely used, instead of deep tillage (0–30 cm), for bean production.

Declaration of Competing Interest

Authors declare that none of us have any conflicts of interest with the submission of the current manuscript to the journal of Soil and Tillage Research.

Acknowledgements

The research was partially supported by the Civilian Research Defense Foundation (CRDF-Global) U.S.-Ukraine competitive grant funding on sustainable agriculture. The USDA Norman Borlaug World Food Prize Fellowship and CRDF-Global provided funding support to Drs.

Nataliia Didenko (Institute of Water Problems and Land Reclamation, Kyiv, Ukraine) and Sergey Lavrenko (Kherson State Agrarian University, Kherson, Ukraine) for their professional development at The Ohio State University, USA.

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