Effects of water absorbing soil amendments on potato growth and soil chemical properties in a semi-arid region

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Abstract: A field experiment was conducted in 2010-2012 in a semi-arid region in northern China to study the effects of synthetic and natural water absorbing soil amendments on potato plant growth and soil chemical properties. A no amendment control, two synthetic water absorbing amendments (potassium polyacrylate-PAA, polyacrylamide-PAM) and a natural amendment (humic acid-HA), were applied annually as single amendments, and in combination (natural plus synthetic). Soil amendment showed a significant ($P \le 0.05$) effect on plant height, stem diameter and leaf area index in the potato growing period in all three years, and improved these plant growth parameters respectively by 0.49%-36.90%, 2.59%-21.12% and 1.85%-37.57%. Soil amendments showed a significant ($P \le 0.05$) effect on soil chemical parameters in different soil layers in all three years, and improved soil organic matter, soil available nitrogen, phosphorus and potassium respectively by 1.03%-11.20%, 0.82%-13.99%, 1.24%-16.61% and 4.50%-22.20%. Soil amendments significantly ($P \le 0.05$) affected fresh tuber yields in the <75 g and 75-150 g size categories; <75 g was decreased by 2.7% to 48.3% (except in 2010) and 75-150 g was increased by 3.5% to 47.6% (except under 45 kg ha^{-1} PAA in 2011). The accumulative effect on soil chemical indicators increased over time with repeated annual application of the amendments in the same field, and the effect of soil amendment on soil chemical indicators was weaken with the increasing soil depth. The PAM+HA amendment always had the greatest effect on plant morphological parameters and soil chemical properties and thus merits further research.

Keywords: soil amendments, potato, plant growth, soil chemical properties, fresh tuber yields

Citation: Xu, S., L. Zhang, L. Zhou, J. Mi, N. B. McLaughlin, and J. Liu. 2018. Effects of water absorbing soil amendments on potato growth and soil chemical properties in a semi-arid region. Agricultural Engineering International: CIGR Journal, 20(2): 9–18.

1 Introduction

Soil is a natural resource which plays a crucial role in terrestrial ecosystems; it is a living and dynamic material, and is non-renewable. It also provides water and nutrients for plant growth, and as such, is a basis to provide a variety of food for human life (Smith, et al., 2015). Soil management strategies alter soil quality and properties and play critical roles in sustainable agriculture (Diacono and Montemurro, 2010). In arid and semi-arid regions, coarse textured soil is usually characterized by low organic matter content due to the low natural vegetation which results in low water holding capacity, inherently low-fertility and vulnerability to erosion (Abdelfattah, 2013; Falkenmark and Rockström, 2004). Soil moisture and nutrient holding capacity are the two key factors for influencing the suitability of soils for crop production (Bhardwaj et al., 2007; Gao et al., 2014). Moreover, due to the arbitrary and inappropriate land use and management, soil in these semi-arid areas has shown continuous degradation and desertification over the past few decades, and the situation is becoming even worse with natural factors of climate change (Biro et al., 2013; Cerdà et al., 2009; Li et al., 2012). In addition to low rainfall, spatial and temporal distribution of rainfall is often very unsuitable for the growth of crops. There is an urgent need to develop adaptive agricultural strategies to

Received date: 2017-09-05 **Accepted date:** 2018-01-17

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mitigate soil quality degradation and stabilize crop production in arid and semi-arid regions (García-Orenes et al., 2009).

Previous research indicated that the use of soil amendments, conservation tillage, mulches and geotextiles were potential strategies to optimize the use of scarce water resources for crop production and maintain good soil properties in the arid and semi-arid regions (Bhardwaj et al., 2007; Giménez-Morera et al., 2010; Roper et al., 2013; Zhao et al., 2014). Application of appropriate soil amendments to increase crop production by improving soil available water and nutrients, has become a viable and practical option to improve the sustainability of dryland agriculture (Bhardwaj et al., 2007; Shaddox, 2004), and it will contribute to the global food security. Moreover, soil amendments can considerably improve soil chemical, physical and biological properties (Hueso-González et al., 2014; Mann et al., 2011), and reduce unfavorable soil stresses in arid and semi-arid areas (Ahmad et al., 2013; Courtney and Harrington, 2012).

Water absorbing amendments incorporated into the soil can improve soil water and nutrient holding capacity, and can help retain any scant or erratic rainfall, reduce evaporation and maintain more plant-available water and nutrients which are released as required for crop growth (Agaba et al., 2010; Farrell et al., 2013; Bouranis et al., 1995; Hüttermann et al., 2009). Both synthetic and natural water absorbing soil amendments are safe and non-toxic to the environment. Indeed, polymers have been investigated and deemed that they are suitable for soil, and will eventually decompose to carbon dioxide, water, and ammonia and potassium ions, without any residue in the whole life cycle (Mikkelsen, 1994; Trenkel, 1997). Some natural water retention soil amendments such as humic acid, can increase macro aggregation, organic carbon, and macronutrients and strengthen the microorganism activity, then to improve the soil properties and nutrient uptake by plants (El-Rehim et al., 2004; Szczerski et al., 2013), and to act as intermediaries that effect antioxidative defense mechanisms (Cordeiro et al., 2011). Furthermore, these soil amendments show a long term effect on soil moisture and nutrient retention up to five years after application before degrading into non-toxic components (Holliman et al., 2005; Trenkel, 1997).

Potato is important cash crop in the semi-arid regions of northern China. It is hypothesized that synthetic or natural water absorbing soil amendments, potassium polyacrylate (PAA), polyacrylamide (PAM) and humic acid (HA) would improve soil productivity by enhancing soil water status in the fragile environment in these regions. Previous publications on the same experiment confirmed the effects of these amendments on potato yield, water use efficiency and cost benefit (Xu et al., 2014), soil physical properties (Xu et al., 2015), potato photosynthesis parameters and tuber quality (Xu et al., 2016a), and soil microbiological parameters (Xu et al., 2016b). Thus, the objective of this study was to evaluate the effectiveness of synthetic and natural water retention soil amendments, in separate or combined operations, on soil chemical properties and potato crop growth parameters in a rain-fed semi-arid region.

2 Materials and methods

2.1 Experimental site and design

The experimental field was located in Dadoupu village (41°10′56″N, 111°36′48″E) of Wuchuan County, approximately 40 km north of Hohhot, Inner Mongolia, in northern China, and the site was marked by the black dot in the Figure 1. It is typical of arid or semi-arid regions with more than 2000 mm mean annual pan evaporation, 350 mm mean precipitation, 3.0°C annual mean temperature, and 125 d frost-free period. The altitude is 1621 m. The soil is sandy loam and alkaline (pH 8.2) containing (g kg^{-1}) 0.97 total nitrogen, 0.026 alkaline nitrogen, 0.0102 available phosphorus, 0.084 available potassium and 8.3 organic carbon.

This experiment was conducted from 2010 to 2012. A randomized complete block (RCB) factorial design with three replications was used and each plot was 30 m^2. The research was in potato phase of an existing oat-potato rotation experiment started in 2006. In this study, soil amendments were two synthetic water absorbing amendments (PAA and PAM) and one natural amendment (HA). These amendments were introduced and described in more details in previous publications on different measurements on the same experimental field site (Xu et al., 2014, 2015, 2016a, 2016b). There were six treatments: CK, control with no amendment application; T1, 45 kg ha^{-1} PAA; T2, 45 kg ha^{-1} PAA + 1500 kg ha^{-1} HA; T3, 45 kg ha^{-1} PAM; T4, 45 kg ha^{-1} PAM + 1500 kg ha^{-1} HA; and T5, 1500 kg ha^{-1} HA. The rates of different soil amendments were determined by preliminary unpublished experiments. T1, T3 and T5 were three single amendment treatments; T2 and T4 were two compound amendments treatments each with a synthetic (PAA or PAM) and a natural (HA) amendment. The same soil amendments were applied in both the potato and oat phases of the rotation each year since 2010. All amendments were applied annually as a single treatment 1 d before potato and oat were planted and were broadcast with fertilizer and incorporated by into the upper 0-20 cm soil layer by cultivating.

Figure 1 The map of the field experiment site

2.2 Experimental procedure

The tillage system was spring cultivate and fall plow. Compound granular fertilizer (17-6-23) was applied at 400 kg ha^{-1} yr^{-1} yielding nutrients of nitrogen (68 kg ha^{-1}), phosphorus (24 kg ha^{-1}) and potassium (92 kg ha^{-1}). This compound granular fertilizer was commonly used by local farmers and was formulated specifically for potato production. Each year, the oat variety was Yanke No.1 and the potato variety was Kexin No.1 in the rotation field. Both cultivars were commonly grown in arid and semi-arid areas in Inner Mongolia. Potatoes were planted following the conventional practice of flat planting (i.e. not ridged) on 16 May 2010, 17 May 2011 and 14 May 2012, and the planting depth was 10 cm, plant spacing was 30 cm and row spacing was 60 cm. Weed control was by manual hoeing when required. Harvest was 130 days after sowing on 22 September 2010, 24 September 2011 and 110 days after sowing on 1 September 2012; harvest was 20 d earlier in 2012 due to an early killing frost on 21 August. The precipitation was 233 mm, 184 mm and 215 mm respectively in 2010, 2011 and 2012. The details on the distribution of rainfall are given by Xu et al. (2015).

2.3 Field and laboratory measurements

In each plot, plant height, stem diameter and leaf area index (LAI) were measured for three randomly selected plants at 50, 70, 90 and 110 days after sowing. LAI data at 110 days in 2012 were missed due to an early killing frost on 21 August. Plant height was measured with a ruler, stem diameter was determined with a Vernier caliper, and a hole punch method was used to estimate total leaf area for one plant for subsequent LAI calculation.

All leaves were removed from one potato plant, and ten randomly selected leaves were laid on top of each other. A 10 mm diameter hole punch was used to randomly punch 5 holes in the same stack of leaves making sure the holes passed through each leaf. LAI was calculated from the combined weight of the 50 leaf disks, and the total weight of all leaves removed from the plant using Equation (1):

$$LAI = \frac{A_{50}W_P}{W_{50}A_p} \qquad (1)$$

where, A_{50} and W_{50} is total the area and weight of the 50 discs with 10 mm dia. (m^2 and g respectively); W_p is the weight of all of the leaves from the plant, and A_p is the ground area occupied by the plant in the field (row spacing × plant spacing, m^2).

Soil samples for soil organic matter, available nitrogen, available phosphorus and available potassium were retrieved manually with a soil auger using the method of Priha and Smolander (1999), at depths of 0-10 cm, 10-20 cm and 20-40 cm at harvest time. Five samples were taken from each plot, mixed to form a single composite sample, air-dried and sieved with 75 mesh sieve (0.20 mm openings). The soil chemical measurement analyses followed the standard procedures according to Page et al. (1982) and Klute (1986). Soil organic matter was measured by dichromate method; soil available nitrogen was determined by a micro-diffusion technique after alkaline hydrolysis, and the ammonium was measured as available N; soil available phosphorus was extracted with 0.5 M $NaHCO_3$ solution (pH 8.5), and determined colorimetrically by the formation of the blue phosphomolybdate complex following reduction with ascorbic acid; soil available potassium was measured by ammonium acetate method with a flame photometer. Each sample was measured three times, and the average value was calculated.

Yield and commercial tuber proportion was measured at maturity. A 10 m^2 area of each plot was harvested by hand for tuber yield. Tubers were manually sorted into three categories, ≥150 g, 75-150 g and <75 g.

2.4 Data analysis

An analysis of variance (ANOVA) was performed using SAS Ver. 9.3 software (SAS Institute Inc., Cary, NC, USA). Tests of significance used the least significant difference (LSD) at $P \leq 0.05$. Mean values are reported in the tables and figures.

3 Results

3.1 Plant morphological measurements

Soil amendment showed a significant ($P \leq 0.05$) effect on all plant morphological parameters including plant height, stem diameter and LAI in the whole potato growing period in 2010, 2011 and 2012 (Figures 2, 3 and 4). Soil amendments improved plant height, stem diameter and LAI respectively by 0.49%-36.90%, 2.59%-21.12% and 1.85%-37.57% compared with the control. There was a similar pattern of the soil amendment effect on morphological parameters at each measurement time after sowing in 2010, 2011 and 2012. The amendments listed in descending order of the effect on plant morphological parameters were T4 > T2 > T3 > T1 > T5 > CK.

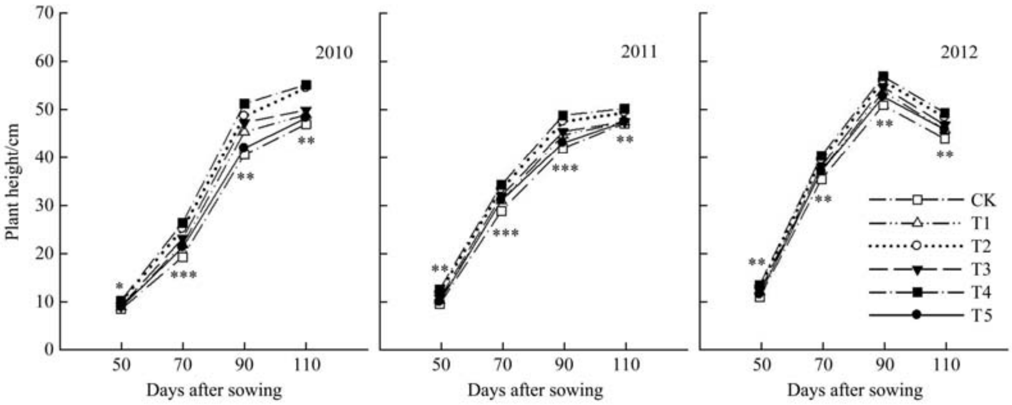

Figure 2 The variation of potato plant height with soil amendments in 2010, 2011 and 2012

Note: *, **, *** Significant at 0.05, 0.01 and 0.001 probability levels respectively. Treatment code: CK, control with no amendment application; T1, 45 kg ha^{-1} PAA; T2, 45 kg ha^{-1} PAA+1500 kg ha^{-1} HA; T3, 45 kg ha^{-1} PAM; T4, 45 kg ha^{-1} PAM+1500 kg ha^{-1} HA; and T5, 1500 kg ha^{-1} HA.

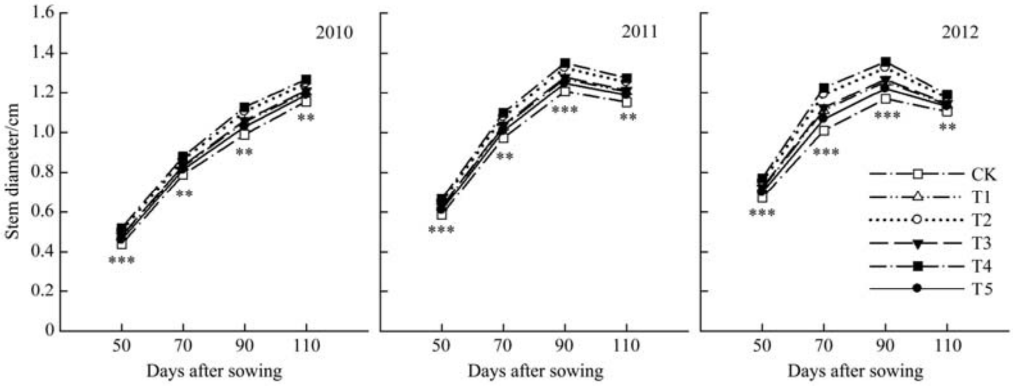

Figure 3 The variation of potato stem diameter with soil amendments in 2010, 2011 and 2012

Note: *, **, *** Significant at 0.05, 0.01 and 0.001 probability levels respectively. Treatment code: CK, control with no amendment application; T1, 45 kg ha^{-1} PAA; T2, 45 kg ha^{-1} PAA+1500 kg ha^{-1} HA; T3, 45 kg ha^{-1} PAM; T4, 45 kg ha^{-1} PAM+1500 kg ha^{-1} HA; and T5, 1500 kg ha^{-1} HA.

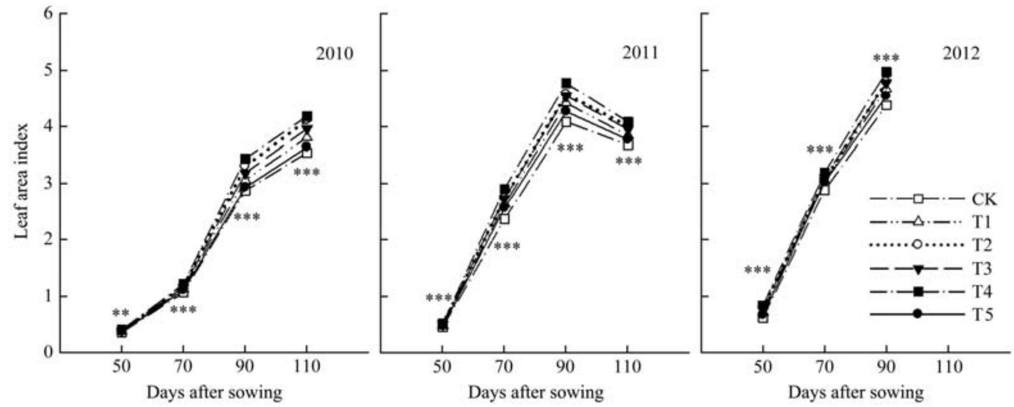

Figure 4 The variation of potato leaf area index with soil amendments in 2010, 2011 and 2012

Note: *, **, *** Significant at 0.05, 0.01 and 0.001 probability levels respectively. Treatment code: CK, control with no amendment application; T1, 45 kg ha^{-1} PAA; T2, 45 kg ha^{-1} PAA+1500 kg ha^{-1} HA; T3, 45 kg ha^{-1} PAM; T4, 45 kg ha^{-1} PAM+1500 kg ha^{-1} HA; and T5, 1500 kg ha^{-1} HA.

3.2 ANOVA of soil chemical measurements

The ANOVA for soil chemical measurements is given in Table 1. The soil amendment treatment (T), year (Y) and soil layer (L) had a highly significant effect ($P \leq 0.01$) on soil organic matter, soil available nitrogen, phosphorus and potassium. The interaction between T and Y and the interaction between T and L had a highly significant effect ($P \leq 0.01$) on all soil chemical parameters. The interaction between Y and L had a highly significant effect ($P \leq 0.01$) on soil available nitrogen and phosphorus but not on soil organic matter and soil available potassium.

Table 1 ANOVA of soil amendment treatments (T), soil layer (L) and year (Y) on potato chemical parameters in 2010-2012

Factor	DF	Organic matter	Available nitrogen	Available phosphorus	Available potassium
T	5	***	***	***	***
Y	2	***	***	***	***
L	2	***	***	***	***
T*L	10	***	***	***	***
T*Y	10	**	***	***	***
Y*L	4	NS	**	***	NS
T*Y*L	20	NS	NS	NS	NS

Note: *, **, *** Significant at 0.05, 0.01 and 0.001 probability levels respectively. NS means not significant.

Variation of soil organic matter, soil available nitrogen, phosphorus and potassium at different soil layers with soil amendment treatments in 2010-2012 is given respectively in Table 2, Table 3, Table 4 and Table 5. Soil amendments showed a significant ($P \leq 0.05$) effect on soil chemical parameters in different soil layers in all three years. Compared with the control, soil amendments improved soil organic matter, soil available nitrogen, phosphorus and potassium respectively by 1.03%-11.20%, 0.82%-13.99%, 1.24%-16.61% and 4.50%-22.20% in three years. The effect of soil amendment on soil chemical indicators was enhanced and accumulated with annual application of the amendments in the same plots over the three years. However, the effect of soil amendment on soil chemical indicators was lower at greater soil depths. Among the single amendment treatments, HA showed a greater result on soil organic matter and potassium, but PAM and PAA showed a greater effect on soil available nitrogen and phosphorus. T4 (PAM + HA) always showed the greatest improvement on soil chemical parameters compared with no amendment control in all three years.

Table 2 Evolution of the content of soil organic matter at different soil layers with soil amendment treatments in 2010-2012 (g kg^{-1})

Soil layer	Treatment	Year 2010	Year 2011	Year 2012
0-10 cm	CK	8.43 c	8.43 e	8.39 d
	T1	8.51 c	8.68 d	8.74 c
	T2	9.02 ab	9.16 bc	9.26 ab
	T3	8.56 c	8.73 d	8.80 c
	T4	9.23 a	9.35 a	9.45 a
	T5	8.83 b	9.01 c	9.10 b
10-20 cm	CK	8.54 c	8.51 b	8.49 b
	T1	8.63 bc	8.67 b	8.70 b
	T2	9.25 a	9.32 a	9.41 a
	T3	8.74 bc	8.78 b	8.80 b
	T4	9.36 a	9.44 a	9.53 a
	T5	8.90 b	9.15 a	9.27 a
20-40 cm	CK	8.41 a	8.40 c	8.38 e
	T1	8.52 a	8.63 c	8.65 d
	T2	8.66 a	8.94 ab	9.06 ab
	T3	8.53 a	8.66 bc	8.73 cd
	T4	8.72 a	9.04 a	9.24 a
	T5	8.62 a	8.71 bc	8.90 bc

Note: Means in the same year and same soil layer followed by the same letters (a, b, c) are not significantly different (P>0.05) according to a protected LSD test. Treatment code: CK, control with no amendment application; T1, 45 kg ha^{-1} PAA; T2, 45 kg ha^{-1} PAA+1500 kg ha^{-1} HA; T3, 45 kg ha^{-1} PAM; T4, 45 kg ha^{-1} PAM+1500 kg ha^{-1} HA; and T5, 1500 kg ha^{-1} HA.

Table 3 Evolution of the content of soil available nitrogen at different soil layers with soil amendment treatments in 2010-2012 (mg kg^{-1})

Soil layer	Treatment	Year 2010	Year 2011	Year 2012
0-10 cm	CK	26.68 b	26.53 c	26.44 d
	T1	27.44 b	27.95 b	28.29 bc
	T2	29.00 a	29.49 a	30.04 a
	T3	27.64 b	28.32 b	28.58 b
	T4	29.29 a	30.06 a	30.37 a
	T5	27.09 b	27.54 bc	27.45 cd
10-20 cm	CK	27.27 d	27.16 d	27.07 d
	T1	28.39 cd	29.30 bc	29.15 bc
	T2	29.59 ab	30.13 a	30.91 a
	T3	28.76 bc	29.68 ab	29.82 b
	T4	29.91 a	30.65 a	31.47 a
	T5	28.06 cd	28.63 c	28.70 c
20-40 cm	CK	27.30 b	27.32 e	27.27 d
	T1	27.85 ab	28.59 cd	29.05 c
	T2	28.22 ab	29.36 ab	30.34 ab
	T3	27.97 ab	28.84 bc	29.40 bc
	T4	28.45 a	29.94 a	30.76 a
	T5	27.53 ab	28.04 d	28.77 c

Note: Means in the same year and same soil layer followed by the same letters (a, b, c) are not significantly different (P>0.05) according to a protected LSD test. Treatment code: CK, control with no amendment application; T1, 45 kg ha^{-1} PAA; T2, 45 kg ha^{-1} PAA+1500 kg ha^{-1} HA; T3, 45 kg ha^{-1} PAM; T4, 45 kg ha^{-1} PAM+1500 kg ha^{-1} HA; and T5, 1500 kg ha^{-1} HA.

Table 4 Evolution of the content of soil available phosphorus at different soil layers with soil amendment treatments in 2010-2012 (mg kg^{-1})

Soil layer	Treatment	Year 2010	Year 2011	Year 2012
0-10 cm	CK	10.28 d	10.23 d	10.17 d
	T1	11.07 b	11.34 b	11.34 b
	T2	11.72 a	11.88 ab	11.98 a
	T3	11.35 b	11.48 b	11.51 b
	T4	11.86 a	12.02 a	12.08 a
	T5	10.77 c	10.83 c	10.89 c
10-20 cm	CK	10.39 c	10.44 d	10.35 d
	T1	11.32 b	11.19 bc	11.54 b
	T2	11.93 ab	12.06 a	12.19 ab
	T3	11.49 b	11.34 b	11.75 b
	T4	12.28 a	12.34 a	12.41 a
	T5	11.01 b	10.90 c	10.99 c
20-40 cm	CK	10.42 c	10.46 d	10.45 d
	T1	10.61 bc	11.06 bc	11.10 bc
	T2	11.07 a	11.64 ab	11.87 ab
	T3	10.74 b	11.20 b	11.33 b
	T4	11.25 a	11.88 a	12.09 a
	T5	10.55 bc	10.67 cd	10.84 cd

Note: Means in the same year and same soil layer followed by the same letters (a, b, c) are not significantly different (P>0.05) according to a protected LSD test. Treatment code: CK, control with no amendment application; T1, 45 kg ha^{-1} PAA; T2, 45 kg ha^{-1} PAA+1500 kg ha^{-1} HA; T3, 45 kg ha^{-1} PAM; T4, 45 kg ha^{-1} PAM+1500 kg ha^{-1} HA; and T5, 1500 kg ha^{-1} HA.

Table 5 Evolution of the content of soil available potassium at different soil layers with soil amendment treatments in 2010-2012 (mg kg^{-1})

Soil layer	Treatment	Year 2010	Year 2011	Year 2012
0-10 cm	CK	85.15 e	85.45 e	85.13 e
	T1	91.34 d	92.68 d	93.29 d
	T2	99.09 ab	100.04 ab	102.85 b
	T3	93.59 cd	95.71 c	96.69 c
	T4	102.03 a	104.84 a	106.65 a
	T5	96.36 bc	97.80 bc	98.76 c
10-20 cm	CK	85.58 e	85.64 e	85.56 e
	T1	92.16 d	94.53 d	95.27 d
	T2	101.66 b	103.00 b	105.85 b
	T3	94.52 d	96.64 d	97.34 d
	T4	105.65 a	107.40 a	109.97 a
	T5	97.78 c	100.01 c	100.95 c
20-40 cm	CK	86.06 e	86.74 e	86.04 f
	T1	90.11 d	91.69 d	92.58 e
	T2	97.57 ab	99.06 ab	100.51 b
	T3	93.30 c	93.47 cd	94.69 d
	T4	98.51 a	101.82 a	102.63 a
	T5	95.98 b	96.95 bc	97.18 c

Note: Means in the same year and same soil layer followed by the same letters (a, b, c) are not significantly different (P>0.05) according to a protected LSD test. Treatment code: CK, control with no amendment application; T1, 45 kg ha^{-1} PAA; T2, 45 kg ha^{-1} PAA+1500 kg ha^{-1} HA; T3, 45 kg ha^{-1} PAM; T4, 45 kg ha^{-1} PAM+1500 kg ha^{-1} HA; and T5, 1500 kg ha^{-1} HA.

3.3 Fresh tuber yield in different tuber size categories

The fresh yield for the <75 g and 75-150 g tuber sizes with soil amendments in 2010-2012 are presented in Table 6. Fresh yield data for >150 g tuber size and total yield were given by Xu et al. (2014). Soil amendments significantly ($P\leq0.05$) affected different size fresh tuber yield in all three years except for <75 g tuber size in 2010. The fresh yield was decreased for <75 g by 2.74%-48.33%, increased for 75-150 g by 3.50%-47.56% except for T1 in 2011, and increased for ≥150 g by 10.40%-77.48% (Xu et al., 2014).

Table 6 Fresh tuber yield of <75 g and 75-150 g tuber size categories for different soil amendments in 2010-2012. Data for total yield, and for yield of > 150 g tuber size are given by Xu et al. (2014)

Treatment		<75 g		75-150 g	
		Fresh tuber yield (mg ha^{-1})	Improvement (%)	Fresh tuber yield (mg ha^{-1})	Improvement (%)
2010	CK	6.05 a	–	4.00 b	–
	T1	5.65 a	–6.70	4.67 a	16.99
	T2	5.77 a	–4.61	4.52 ab	13.02
	T3	5.59 a	–7.65	4.49 ab	12.46
	T4	5.20 a	–14.15	4.97 a	24.49
	T5	5.82 a	–3.87	4.50 ab	12.62
2011	CK	6.84 a	-	1.96 b	-
	T1	6.18 b	–9.61	1.89 b	–4.02
	T2	5.23 bc	–23.54	2.03 b	3.50
	T3	5.22 bc	–23.67	2.34 b	19.01
	T4	4.70 c	–31.38	3.04 a	54.95
	T5	6.18 ab	–9.60	2.41 ab	22.78
2012	CK	5.96 a	-	2.39 c	-
	T1	4.87 ab	–18.34	3.19 ab	33.74
	T2	4.07 b	–31.70	2.77 bc	16.24
	T3	4.17 ab	–29.96	2.95 abc	23.51
	T4	3.08 b	–48.33	3.52 a	47.56
	T5	5.80 a	–2.74	2.84 bc	18.87

Note: Means in the same column and year, and followed by the same letter are not significantly different (P>0.05) according to a protected LSD test. Treatment code: CK, control with no amendment application; T1, 45 kg ha^{-1} PAA; T2, 45 kg ha^{-1} PAA+1500 kg ha^{-1} HA; T3, 45 kg ha^{-1} PAM; T4, 45 kg ha^{-1} PAM+ 1500 kg ha^{-1} HA; and T5, 1500 kg ha^{-1} HA.

4 Discussions

The data showed that water absorbing soil amendments had a significant ($P \leq 0.05$) effect on potato morphological measurements and improved these parameters at different measurement times after sowing in 2010-2012 (Figures 2, 3 and 4), which is consistent with the decrease in <75 g tuber size yield, and increase in 75-150 g, >150 g, and total tuber yield (Table 6, Xu et al., 2014). Morphological measurements such as plant height, stem diameter and LAI, are indicators of potential productivity and are highly correlated with potato tuber yield (Deblonde and Ledent, 2001). Similar positive correlations have been shown on morphological measurements and productivity of other crops with different soil amendments, such improved grass and rice performance with biochar (Jones et al., 2012), strong influence on tomato morphology by compost and vermicompost (Lazcano et al., 2009), and enhanced corn growth with different superabsorbent polymers (Islam et al., 2011).

In this experiment, soil amendment showed a significant ($P \leq 0.05$) effect on soil chemical indicators and improved these parameters in different soil layers in all three years (Tables 2, 3, 4 and 5). This was in agreement with other studies where soil chemical properties were improved by biochar, composted sewage sludge, superabsorbent polymer and manure (Awad et al., 2012; Bai et al., 2010; Cheng et al., 2007; Jones et al., 2012; Liu et al., 2010; Uzoma et al., 2011). Previous results indicated that soil amendments could effectively increase the cation holding capacity in the soil, enhance the absorption of cations such as NH_4^+ and K^+ (Achtenhagen and Kreuzig, 2011). This reduced the fertilizer loss and improved the soil capacity for crop production (Xie et al., 2011). Moreover, soil amendments promoted the fertilizer uptake and utilization and improved the fertilizer use efficiency (Dorraji et al., 2010; El-Rehim et al., 2004; Syvertsen and Dunlop, 2004). For the single amendments, HA showed a better result on soil organic matter and potassium than PAA or PAM, which might be due to the HA containing large amounts of organic carbon and potassium. In contrast, PAM and PAA showed a better effect on soil available nitrogen and phosphorus, which might be related to the cation adsorption characteristics of synthetic soil amendments. PAM showed a better effect than PAA, this might be that nitrogen has a greater effect on potato growth compared with potassium. Soil nitrogen and potassium will increase with the decomposition of both PAM and PAA but PAM contains an amino group while PAA contains K^+. PAM and HA compound treatment showed the best result in retaining soil nutrients, which may due to the doubling of the amendment effect, or the combination of synthetic and natural soil amendments providing an enhanced effect, improving both soil organic carbon and soil water together, providing a better soil condition for soil microorganism activity and nutrient cycling (Bhardwaj et al., 2007; Cordeiro et al., 2011; Hüttermann et al., 2009). The mechanism of the interaction between synthetic and natural soil amendments needs more research in the future.

With the annual amendment application in the same plots, the amendments accumulated and their effects were enhanced over time. The soil amendments are not degraded completely by soil microorganisms within one year. A single application of water absorbing soil amendments has been shown to retain soil moisture and nutrients up to five years, but the effect showed a decreasing trend over the five years (Holliman et al., 2005; Trenkel, 1997). We applied soil amendments annually in our experiments, and this might be the reason for the consistent enhanced and accumulated effect of soil amendments in the later years. Meanwhile, the effect of soil amendment on soil chemical indicators declined with the increasing soil depth, this might be related the different amount of soil amendments in different soil layers. Soil amendments were applied annually as a single treatment broadcast with fertilizer before seeding and incorporated to a depth of 20 cm by cultivating. Thus, most soil amendments were concentrated in upper soil layer (0-20 cm), and only mixed with the deeper soil layer by fall ploughing each year. However, our results are based on a short-term experiment over three years, the long-term effect of soil amendments on soil chemical properties needs to be explored in the future.

Soil amendments improved potato yield with the same amount of fertilizer indicating improved fertilizer use efficiency and reduced nutrient loss and groundwater pollution by the leaching in the rainy season (Magalhaes et al., 1987). This will be beneficial for protecting the fragile environment in arid and semi-arid areas, and will also contribute to sustainable agriculture in these regions.

5 Conclusion

It was observed that the application water absorbing soil amendments improved soil chemical properties and promoted potato growth, and contributed to the sustainability of agricultural crop production in semi-arid regions. With annual application, the effect of soil amendment on soil chemical indicators was enhanced and accumulated. The effect of soil amendment on soil chemical indicators was lower with the increasing soil depth, likely due to a smaller amount of amendment in deeper soils. The combination of PAM synthetic amendment and HA natural amendment (treatment T4) had the greatest effect among all amendment treatments.

Further studies on the long-term effect of soil amendments are required to develop a more complete understanding of long-term effect of the interaction between soil amendments, soil microbiology and plants. A more complete understanding would form the basis for development of management strategies for improvement of soil and crop production in semi-arid areas.

Acknowledgements

The authors acknowledge financial support from the National Natural Science Foundation of China 'Mechanism of soil water preservation with application drought resistant agent' (number 31160267), 'Mechanisms of cover plants on soil microbial community structure and productivity of banana cropping system' (number 31600349), Inner Mongolia Science and Technology Project "Inner Mongolia Grains Engineering Technology Research", Inner Mongolia "Prairie Excellence" Project and the MOE-AAFC PhD Research Program sponsored by Ministry of Education of the People's Republic of China and Agriculture and Agri-Food Canada.

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