Evaluation of synthetic and natural water absorbing soil amendments for potato production in a semi-arid region

S.T. Xu[1, 2], L. Zhang[3], N. B. McLaughlin[2], J. Z. Mi[1], Q. Chen[4], J. H. Liu[1*]

(1. *Oat Scientific and Technical Innovation Team, Inner Mongolia Agricultural University, Hohhot, Inner Mongolia, 010019, China*;
2. *Eastern Cereal and Oilseed Research Centre, Agriculture and Agri-Food Canada, Ottawa, ON, K1A 0C6, Canada*;
3. *Industrial Crop Research Institute, Yunnan Academy of Agricultural Sciences, Kunming, Yunnan, 650205, China*;
4. *College of Agronomy, Northwest A&F University, Taicheng Road 3#, Yangling 712100, Shaanxi, China*)

Abstract: Effect of synthetic and natural water absorbing soil amendments on soil moisture content, yield and water use efficiency (WUE) of potato production was investigated in a field experiment in a semi-arid region in northern China in 2010-2012. Treatments included two different water absorbing synthetic amendments (potassium polyacrylate-PAA, polyacrylamide-PAM) and one natural amendment (humic acid-HA), both as single amendments, and compound amendments (natural combined with a synthetic) and no amendment control. Soil amendments significantly ($P \leq 0.05$) affected soil moisture content over the entire potato growing season, particularly in the 0-40 cm layer, except for periods with adequate precipitation. Soil amendments increased fresh tuber yield by 6.2%-23.6%, 4.2%-32.9%, and 12.0%-26.2%, improved commercial tuber proportion of the total yield by 1.7%-10.1%, 3.2%-16.6%, and 2.9%-13.7% and increased WUE by 11.1%-23.8%, 4.1%-34.7%, and 19.8%-38.6% in 2010, 2011, and 2012 respectively. The compound treatment, PAM plus HA, had the highest soil water content, yield and WUE in all three years. Cost benefit analysis based on present amendment costs and potato prices, showed that the single synthetic amendment PAM had the highest economic return in all three years; economic return was improved by 138, 413, and 795 USD/ha in 2010, 2011, and 2012 respectively compared with the non-application control. The PAM plus HA treatment shows the most promise in improving soil water holding capacity and potato production, and deserves further research.

Keywords: soil amendments, potato, soil moisture content, yield, water use efficiency, economic return

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1 Introduction

Drought is one of the most severe threats to sustainable agricultural crop production in the conditions of changing climate worldwide, with potentially devastating economic and sociological impact (Rivero et al., 2007). It is one of the major causes of crop loss worldwide, reducing average yields for most major crops by more than 50% (Buchanan et al., 2000; Wang et al., 2003). A great challenge faced by political and scientific leaders in the 21st century will be to increase the world's food supply to accommodate a world population growing to 10 billion or more people while also facing climate change (Easterling, 2007). Therefore, water scarcity, particularly in arid and semi-arid regions, is viewed as a major threat to long-term food security (Zhang et al., 2014). Furthermore, drought episodes will become more frequent because of the long-term effect of global warming (Salinger et al., 2005), emphasizing the urgent need to develop adaptive agricultural strategies for a changing environment. At present, the arid and semi-arid regions account for about one-third of the global total land area (Archibold, 1995).

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Corresponding author: J. H. Liu, Oat Scientific and Technical Innovation Team, Inner Mongolia Agricultural University, Hohhot, Inner Mongolia, 010019, China. Tel: (+86)13848150459. Email: cauljh@aliyun.com.

Agro-ecosystems in arid and semi-arid regions are characterized by considerable challenges: periods of high rainfall followed by long periods of little or no rain, intermittent dry spells, recurrent drought years, high evaporative demand and often soils with inherently low-fertility which are vulnerable to erosion (Falkenmark and Rockström, 2004). Moreover, the situation is deteriorating concomitantly with the climate change. The problem of inefficient use of rainfall by crops is of great importance in semi-arid and arid regions, where water shortage frequently occurs and water is often the main limiting factor determining the productivity of crops (Bhardwaj et al., 2007; Islam et al., 2011; Zhao et al., 2014).

Population and water demands continue to grow aggravating the problem of water scarcity (Postel et al., 1996; Bouwer, 2002). It is a challenge to both scientists and humanitarian organizations, to cope with scarce supplies at present, and more so in the future. There is potential for improving WUE in many field crops but there is insufficient information for defining the best strategy for coping with water deficit in many situations and existing management strategies are not enough to ensure sustainable production. As a component of crop drought resistance under stress, WUE is often considered as an important determinant of yield (Blum, 2009). Good soil-water management is the most important factor of agricultural production in arid and semi-arid areas (Debaeke and Aboudrare, 2004). In arid and semi-arid climates with high growing season temperatures and low annual and growing season precipitation, new crop water management strategies are needed to stabilize the production. In addition to low rainfall, spatial and temporal distribution is very unsuitable for the growth of crops.

Applying water absorbing chemical materials to soils may be a viable alternative and practical strategy for solving the problems of limited and intermittent rainfall. These soil amendments can improve soil physical and chemical properties and soil nutrient status, and have a positive impact on soil microorganisms to improve soil productivity (Mann et al., 2011). Synthetic chemical polymers that absorb water, sometimes 400 times or more than their own weight, have been investigated as soil amendments to improve soil water holding capacity (Bouranis et al., 1995; Huettermann et al., 2009). When polymers are incorporated into the soil, they retain large quantities of water and nutrients, which are released as required by the plant. Thus, plant growth could be improved with limited water supply in the arid and semi-arid regions (Bhardwaj et al., 2007; Islam et al., 2011). It was reported that polymer addition to sandy soil increased water and fertilizer use efficiency for plants (Bhardwaj et al., 2007; Islam et al., 2011). Moreover, the germination process, plant growth, nutrient uptake, yield and both the water and fertilizer use efficiency were increased by hydrogels in sandy soil (El-Rehim et al., 2004; Syvertsen and Dunlop, 2004; Dorraji et al., 2010). Furthermore, polymers potentially influence infiltration rates, density, soil structure, compaction, aggregate stability, crust hardness, and evaporation rates (Sepaskhah and Bazrafshan-Jahromi, 2006). Indeed, polymers that have been investigated and deemed suitable for soil amendments are considered safe and non-toxic and will completely decompose to carbon dioxide, water, and ammonia and potassium ions, (Mikkelsen, 1994; Trenkel, 1997). Moreover, these polymers can retain soil moisture and fertilizer up to five years after application before degrading into non-toxic components (Trenkel, 1997; Holliman et al., 2005). Previous research indicated that application of polymers not only prevents pollution of agro-ecosystem, but also increases farmers' economic return (Islam et al., 2011). Another potential natural amendment is natural such as humic acid which can increase water availability for crops in arid and semi-arid water stressed soils (Turan et al., 2011). It also acts as an intermediary that affects anti-oxidative defense mechanisms (Cordeiro et al., 2011), and improves unfavourable soil properties and nutrient uptake by increasing macro aggregation, organic carbon, and macronutrients and also results in a short-term increase in electrical conductivity levels (El-Rehim et al., 2004; Szczerski et al., 2013). By applying some of the soil amendments such as super absorbent polymers and HA, it may be possible to maintain good soil moisture under erratic rainfall and optimize use of water resources for crop production in the arid and semi-arid regions.

The objective of this study was to evaluate the effectiveness of synthetic and natural water retention soil amendments with single and compound amendment treatments for potato production in a rain-fed field in an arid and semi-arid region.

2 Materials and methods

2.1 Soil amendments

Potasium polyacrylate (PAA) is a high molecular weight synthetic polymerand is light yellow in colour, and granular. It is highly hydroscopic and absorbs as much as 400 times its mass in water, releasing 95% back into the root system. It has a wide variety of commercial and industrial uses, including an absorbent in baby diapers and featured in the maximum absorbency garment used by National Aeronautics and Space Administration (NASA). Its density is about 1.09 g/cm^3. It is soluble in water, ethanol and isopropanol, and easily decomposes above 300℃ and slowly decomposes at room temperatures. It was purchased from Dongying Huaye New Materials Co., Ltd, Dongying, Shandong, China and the cost was 4.0 USD/kg.

Polyacrylamide (PAM) is also a high molecular weight synthetic polymer which is a white powder. It is highly hydroscopic. Density is about 1.30 g/cm^3. It is soluble in water, but almost insoluble in organic solvents, and it easily decomposes above 120℃. Polyacrylamide is not toxic, however unpolymerized acrylamide, which is a neurotoxin, can be present in very small amounts in the polymerized acrylamide. Therefore it is necessary to handle it with caution. The anionic form of cross-linked polyacrylamide is frequently used as a soil conditioner on farm land and construction sites for erosion control. More recently, it has been used as subdermal filler for aesthetic facial surgery. It was produced by Dongying Huaye New Materials Co., Ltd, Dongying, Shandong, China. The cost was 4.8 USD/kg.

Humic acid (HA) is a natural occurring substance in the soil, and is a bio product of organic matter decomposition. It can be synthesized by pulverizing lignite. HA produces various morphological, physiological, and biochemical effects through the interaction with physiological and metabolic processes (Cordeiro et al., 2011). HA acts in plants via a specific form of stress that is detected by anti-stress defense systems in plants. HA was dissolved and supplied with the nutrient solution to plants, which can protect against water stress in degraded soils (García et al., 2012). In non-clay, arid and sandy soils, HA increases water availability to plants, and improves unfavourable salt stress in soil, plant productivity and nutrient uptake (Turan et al., 2011). HA was made by Yongye Group Co., Ltd, Hohhot, Inner Mongolia, China; the free humic acid was around 38.3%, and the price was 0.3 USD/kg.

2.2 Experimental site and design

The experimental field was located in Dadoupu village (41°10′N, 111°36′E) of Wuchuan County, Hohhot, Inner Mongolia, China. It is typical of arid and semi-arid regions. The mean precipitation is about 350 mm, mean annual pan evaporation at the site is more than 2,000 mm, mean temperature is 3.0℃, frost-free period is around 125 d, and altitude is 1621 m. The soil is sandy loam and alkaline (pH 8.2) containing (g/kg) 8.3 organic carbon, 0.97 total nitrogen, 0.026 alkaline nitrogen, 0.0102 available phosphorus, and 0.084 available potassium.

This experiment was a randomized complete block (RCB) factorial design with three replications; each plot was 30 m^2. The study was conducted in potato phase from 2010-2012 of oat-potato rotation field started in 2006. In this study, there were five treatments consisting of different combinations of water absorbing soil amendments: control with no amendment application (CK), 45 kg/ha PAA (T1), 45 kg/ha PAA plus 1,500 kg/ha HA (T2), 45 kg/ha PAM (T3), 45 kg/ha PAA plus 1,500 kg/ha HA (T4) and 1,500 kg/ha HA (T5). T1, T3 and T5 were single amendment treatments; T2 and T4 were compound amendments treatments each with two amendments. The rate of different soil amendments was determined by previous unpublished research in our laboratory. The same soil amendments were applied in both oat and potato phases of the rotation each year since 2010. All amendments were applied annually as a single treatment and were broadcast with fertilizer prior to seeding and incorporated into the soil by cultivating.

2.3 Experimental protocol

The tillage system was fall plow and spring cultivate. Each plot was applied with nitrogen (68 kg/ha), phosphorus (24 kg/ha) and potassium (92 kg/ha) by compound granular fertilizer (17-6-23) at the rate of 400 kg ha^{-1} yr^{-1}. The compound granular fertilizer was specialized for potato; it was used by local farmers. Each year, the potato variety was Kexin No.1 and the oat variety was Yanke No.1 in the rotation field; both cultivators were commonly grown in arid and semi-arid regions in Inner Mongolia. Both the potatoes and oats were planted by planter with conventional flat planting (i.e. not ridged) on May 16, 2010, May 17, 2011 and May 14, 2012. The tuber seed pieces were placed 10 cm deep with plant spacing 30 cm and row spacing 60 cm. Weed control was by manual hoeing when required. Harvest was in late September, 130 d after sowing; harvest was 20 d earlier (110 d after planting) in 2012 due to an early frost.

2.4 Climate parameter measurement

Growing seasonal daily precipitation data were determined by rain gauge installed in the experimental field. Daily mean temperature data were obtained from the China Meteorological Administration in the nearest weather station located in Siziwang Banner, Ulanqab, Inner Mongolia, about 40 km from the field site.

2.5 Field and laboratory measurements

Soil moisture content was periodically measured by the depth and time variation with gravimetric method. Soil samples were retrieved manually with a soil auger, at depths of 0-10, 10-20, 20-40, 40-60, 60-80, and 80-100 cm at 0, 50 70, 90, 110, and 130 d after sowing. The samples were packed in aluminum boxes and oven-dried at 105℃ until constant weight.

Soil bulk density was measured each year prior to seeding. A pit was excavated with ledges at 5, 15, 30, 50, 70, and 90 cm depths. A 5 cm diameter by 5 cm cutting ring was inserted to remove soil samples for bulk density measurements.

Yield and commercial tuber proportion was measured at maturity. A 10 m^2 area of each plot was harvested by hand for tuber yield and quality. Tubers were manually sorted into commercial tubers ≥150 g, and utility tubers <150 g. Dry tuber yield was determined by drying the tuber sample in a forced air oven at 70℃ for 72 h.

2.6 Data analysis

Soil water storage (*SWS*) was calculated by Equation (1):

$$SWS = d\, c\, \rho_s\, \rho_w^{-1} \tag{1}$$

where, d is soil depth, mm; c is gravimetric soil moisture content; ρ_s is soil bulk density; ρ_w is water density.

Water evapotranspiration (*ET*) was calculated by Equation (2) given by (Chu et al., 2009).

$$ET_{1\text{-}2}=10\Sigma\rho_i H_i\,(\theta_{i1}-\theta_{i2})+M+P_0+K \tag{2}$$

where, $ET_{1\text{-}2}$ is period water evapotranspiration, mm; i is soil layer (i =1, 2…, n); ρ_i (g/cm^3) is soil bulk density of the i^{th} soil layer; H_i is the depth of the i^{th} soil layer; θ_{i1} and θ_{i2} is soil moisture content of the beginning and end of the time period of the i^{th} soil layer; M (mm) is water added by irrigation during the period, (no irrigation was used so M = 0 in this study); P_0 (mm) is the total precipitation during growing season; K (mm) is the change in ground water during the period. The experimental field was flat with no water added by runoff from higher elevations, and measurement showed no change in the water table so $K = 0$ for this study.

Water use efficiency (*WUE*) was calculated by Equation (3)

$$WUE = Y\, ET_\alpha^{-1} \tag{3}$$

where, Y (kg/ha) is the total (commercial plus utility) dry tuber yield of potato, and ET_α (mm) is the total whole growing season water evapotranspiration determined from Equation (2).

Cost-Benefit analysis was conducted to assess the economics of using the water absorbing soil amendments. The input (I) is cost of soil amendments given by Equation (4).

$$I\,(\text{USD ha}^{-1}) = P_a R_a \tag{4}$$

where, P_a (USD/kg) is the price of different soil amendments; R_a is the application rate (kg/ha) of different soil amendments. For the compound amendment treatments (T2 and T4) input cost included both amendments. Input cost only included the cost of the soil amendments; it did not take into the other costs (fertilizer, fuel etc.), as these costs would be the same for all amendment treatments.

Output (O) was the yield of each of commercial and utility tubers multiplied by their respective prices:

$$O\ (\text{USD/ha}) = P_c\, Y\, R_c + P_u\, Y\, R_u \tag{5}$$

where, Y is total fresh tuber yield; P_c is the 10 years' average price of commercial tuber (0.3 USD/kg); R_c is proportion of commercial tuber; P_u is the 10 years' average price of utility tuber (0.1 USD/kg), and R_u is utility tuber proportion of the total tuber yield. The same amendment cost and tuber price was used for the cost benefit analysis in each of 2010, 2011, and 2012.

Benefit (B) was calculated by Equation (6).

$$B\ (\text{USD ha}^{-1}) = O - I \tag{6}$$

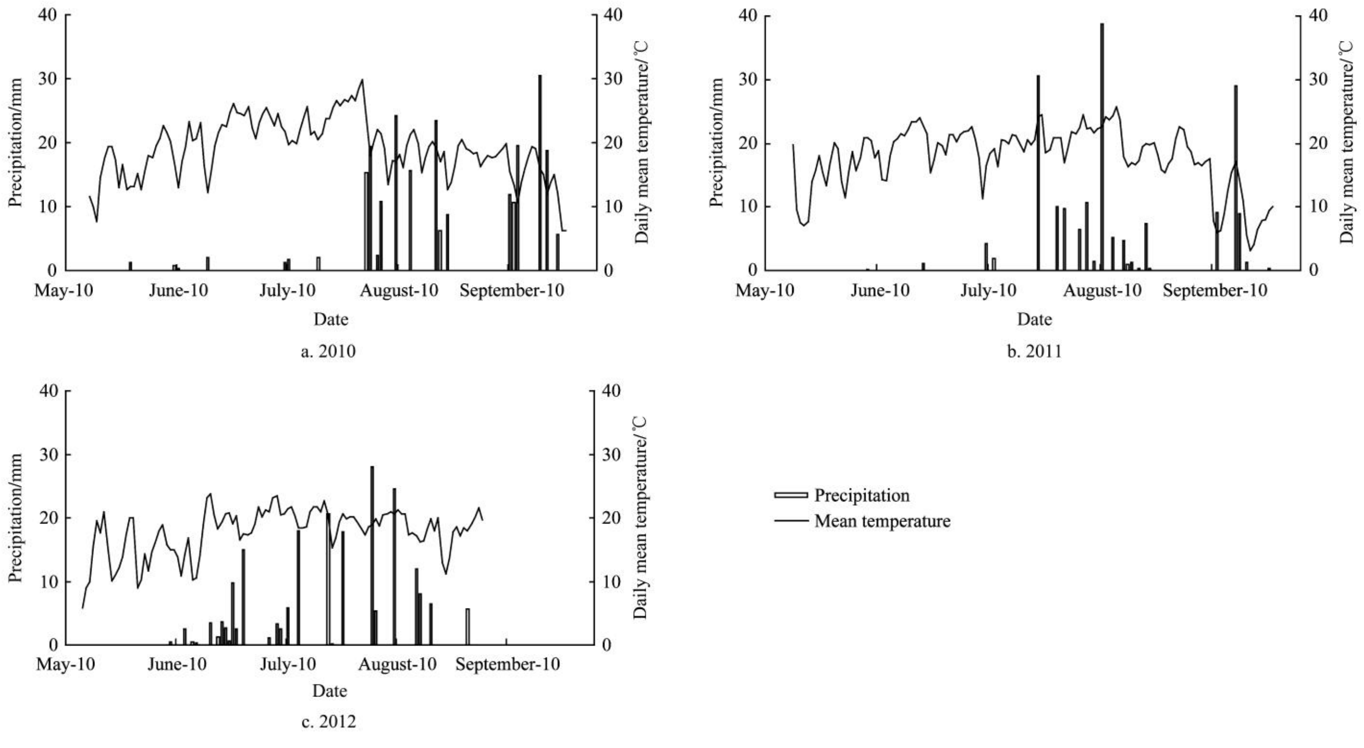
This cost-benefit analysis provides an estimate of additional return (or loss) for the amendments over that for the control treatment.

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

3 Results

3.1 Precipitation and daily mean temperature

Total precipitation during potato growing season is shown in Figure 1. In both 2010 and 2011 it was dry in the early part of the growing season. In 2010 it was initially dry with high temperatures, but there was plentiful rainfall late in the growing season, while 2011 had plentiful rainfall only in the middle of the growing season in 2011, whereas rainfall distribution in 2012 was more uniform throughout the growing season, a situation that was good for potato production. However, there was a killing frost on August 21, 2012, which was unusual, and severely affected the potato crop.



a. 2010

b. 2011

c. 2012

Figure 1 Daily mean temperature and rainfall distribution during potato-growing season in 2010-2012 at the experimental station in Wuchuan, Hohhot, Inner Mongolia, China

3.2 Soil moisture content

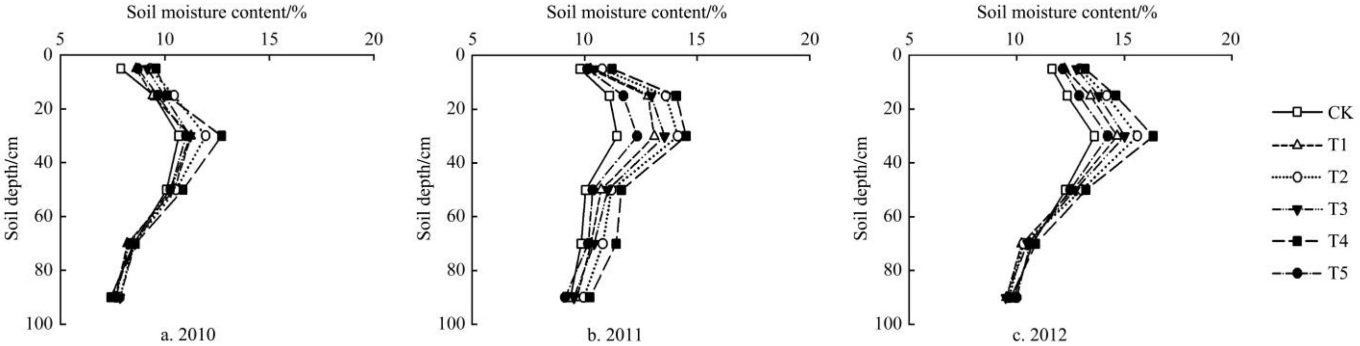
The ANOVA for soil moisture content in 2010, 2011, and 2012 are given in Table 1. The amendment treatment effect on soil moisture content had different levels of significance at different sampling times. Soil layer always had highly significant effect ($P \leq 0.01$) on soil moisture content. In contrast, the interaction between treatment and soil layer had no significant effect. The amendment treatment effects on soil moisture content were directly related to precipitation and evaporation. In 2010, treatment had a significant effect ($P \leq 0.05$) after sowing, and had highly significant effect ($P \leq 0.01$) in the late growing season, corresponding to the high temperature and low precipitation in the early growing season and intermediate rainfall late in the growing season. In 2011 and 2012, the treatment effect was not significant at several sampling times due to adequate rainfall prior to sampling. The treatment effect was reduced in extreme weather, both when rain was plentiful, and during droughty periods. Significance of soil layer on soil moisture content was expected as there are normally large differences in soil moisture content at different layers.

Table 1 ANOVA of effect of water absorbing soil amendment treatments and soil layer depth on soil moisture content at six sampling dates in 2010-2012

Factor	DF	Days after sowing					
		0	50	70	90	110	130
2010							
Amendment	5	NS	*	*	*	***	***
Soil layer	5	***	***	***	***	***	***
Treatment Soil layer	25	NS	NS	NS	NS	NS	NS
2011							
Amendment	5	**	**	***	NS	*	**
Soil layer	5	***	***	***	***	***	***
Treatment Soil layer	25	NS	NS	NS	NS	NS	NS
2012							
Amendment	5	**	*	NS	NS	**	-
Soil layer	5	***	***	***	***	***	-
Treatment Soil layer	25	NS	NS	NS	NS	NS	-

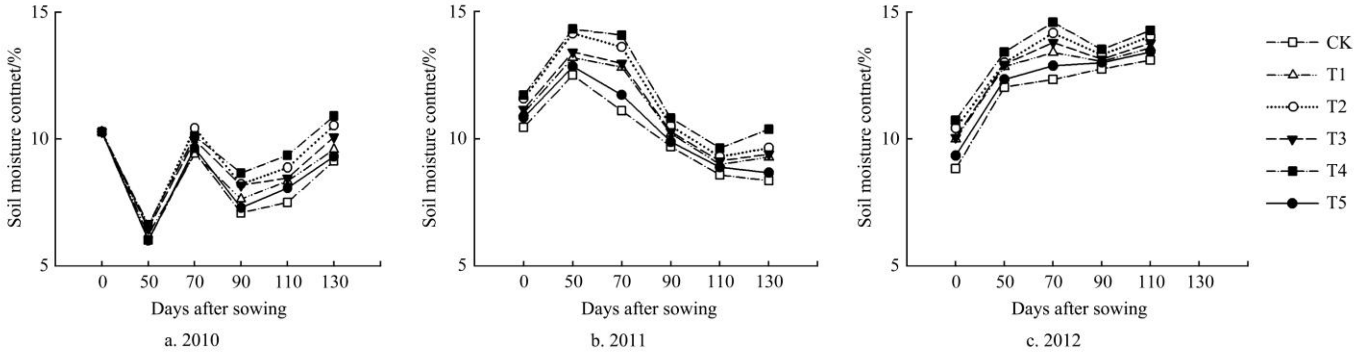
Note: *, **, *** Significant at 0.05, 0.01 and 0.001 probability levels. NS means not significant.

The vertical variation of the soil moisture content at 70 d after sowing in 2010, 2011, and 2012 are given in Figure 2. Tuber initiation stage of potato occurs about 70 d after planting; vigorous growth occurs during this stage and the plant has high requirements for water and nutrients. Availability of water and nutrients during this stage, affects the potato tuber number, size and weight, and potato tuber yield (Claassens and Vreugdenhil, 2000). Soil water content was always highest in 20-40 cm layer. The T4 treatment always had the highest soil water content of the soil amendments and the difference among amendments was the greatest at the 20-40 cm layer (Figure 2). Temporal variation of soil water content at the 10-20 cm layer was different in each of the three years and reflected the different seasonal rainfall patterns in each year (Figures 1 and 3). Periods of high precipitation and dry periods both resulted in small differences in soil moisture among the treatments, but when precipitation was intermediate, the difference was much greater and the amendment effect was significant (Table 1, Figure 3). The T4 treatment consistently produced the highest soil moisture content at the 20-40 cm layer.



a. 2010 b. 2011 c. 2012

Figure 2 Vertical variation of soil moisture content at 70-d after sowing in 2010-2012.
Treatment code: CK, no amendment control; T1, PAA; T2, PAA plus HA; T3, PAM; T4, PAM plus HA; T5, HA



a. 2010 b. 2011 c. 2012

Figure 3 Temporal variation of soil moisture content at 10 to 20-cm layer in 2010-2012.
Treatment code: CK, no amendment control; T1, PAA; T2, PAA plus HA; T3, PAM; T4, PAM plus HA; T5, HA

3.3 Tuber yield and commercial tuber proportion

The fresh tuber yield for all soil amendments except T5 was significantly ($P\leq0.05$) greater than that for CK for all of 2010, 2011, and 2012 (Table 2). The fresh tuber yield for the amendment treatments increased by 6.2%-23.6%, 4.2%-32.9%, and 12.0%-26.2% respectively in 2010, 2011, and 2012 over that for CK, T4 had the highest fresh tuber yield with 22.6, 23.5, and 29.0 Mg/ha in 2010, 2011, and 2012 respectively. Commercial tuber proportion exhibited a pattern similar to fresh tuber yield, soil amendments increased commercial tuber proportion by 1.7%-10.1%, 3.2%-16.6%, and 2.9%-13.7% respectively in 2010, 2011, and 2012 compared to CK, and T4 resulted in the highest commercial tuber proportion of 55.3%, 66.8%, and 77.4% in 2010, 2011, and 2012 respectively. Both fresh tuber yield and commercial yield had a similar regular pattern, and the sequence listed in descending order was T4 > T2 > T3 > T1 > T5 > CK. There was a general trend for higher fresh tuber yield for the compound amendment treatments (T4 and T2) than for the single amendment treatments (T1, T3, and T5) but the difference was not always significant (Table 2) .

Table 2 Fresh tuber yield and commercial tuber proportion for different water absorbing soil amendments in 2010-2012

Treatment	Fresh tuber yield, Mg/ha	Increase in yield as a percent of the control treatment, %	Commercial tuber proportion, %
		2010	
CK	18.3 (1.0) d	-	45.2 (4.2) b
T1	20.5 (1.1) bc	11.8	49.7 (3.1) ab
T2	21.6 (1.1) ab	17.9	52.4 (3.6) ab
T3	20.6 (0.9) bc	12.2	51.0 (5.7) ab
T4	22.6 (1.5) a	23.6	55.3 (5.6) a
T5	19.5 (0.7) cd	6.2	47.0 (3.3) b
		2011	
CK	17.7 (0.6) c	-	50.3 (1.8) d
T1	19.6 (1.2) bc	11	59.0 (3.4) bc
T2	20.2 (0.1) b	14.1	64.0 (0.3) ab
T3	20.0 (1.7) b	12.8	61.9 (5.0) ab
T4	23.5 (1.8) a	32.9	66.8 (5.1) a
T5	18.4 (0.6) bc	4.2	53.4 (1.8) cd
		2012	
CK	23.0 (2.4) b	-	63.6 (2.6) d
T1	27.3 (1.7) a	18.9	70.5 (0.4) bc
T2	28.7 (1.3) a	24.8	76.1 (2.7) ab
T3	28.0 (1.6) a	21.9	74.5 (2.2) ab
T4	29.0 (3.1) a	26.2	77.4 (2.3) a
T5	25.7 (2.0) ab	12	66.5 (6.9) cd

Note: The different letters (a, b, c) are significantly different at $P\leq0.05$ according to a protected LSD test. Numbers in brackets are standard deviation. Treatment code: CK, no amendment control; T1, PAA; T2, PAA plus HA; T3, PAM; T4, PAM plus HA; T5, HA.

3.4 Water use efficiency (WUE)

In 2010, WUE with soil amendments was significantly ($P\leq0.05$) higher than that in CK (15.4 kg ha^{-1} mm^{-1}) except T5, but there were no significant differences ($P>0.05$) among the five treatments (Figure 4). WUE increased by 11.1%-23.8% over that for CK. In 2011, the compound amendment T4 (31.4 kg/ha/mm) was significantly ($P\leq0.05$) higher than that in both T2 (26.5 kg/ha/mm) and CK (22.8 kg/ha/mm), but there were no significant differences ($P>0.05$) between the other three treatments and CK (22.8 kg/ha/mm), mostly because the scant precipitation early in the growing season. WUE with the soil amendments increased by 4.1%-34.7% except T5, which showed a decrease (not significant) in WUE over that for CK. T4 had the highest WUE with 31.4 kg/ha/mm. In 2012, WUE for all the five soil amendments treatments were significantly ($P\leq0.05$) higher than that in CK (15.6 kg/ha/mm), but there were no significant differences ($P\geq0.05$) among the amendments. The WUE increased by 19.8%-38.6% with soil amendments over that for CK. Over the three years, there was a consistent trend for compound amendment treatments to have higher WUE than for single amendment treatments, but the differences were not significant ($P>0.05$).

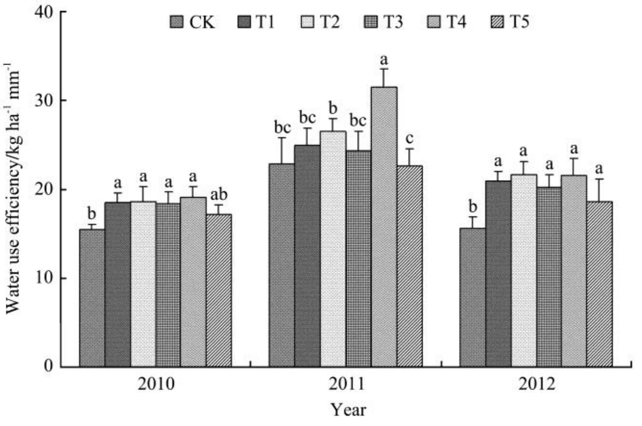


Figure 4 Water use efficiency of dry tubers with soil amendments in 2010-2012. Treatment code: CK, no amendment control; T1, PAA; T2, PAA plus HA; T3, PAM; T4, PAM plus HA; T5, HA. Small bar shows standard deviation. Bars within the same year and with the same letters are not significantly different at $P = 0.05$ according to a protected LSD test

3.6 Cost - Benefit analysis

In 2010, only T1 and T3 improved the economic return while the other three amendment treatments reduced the economic return. Using T1 and T3 the return was increased by 126 and 138 USD/ha respectively compared with CK (Table 3). In 2011, the returns were better than 2010. There were three treatments (T1, T3 and T4) with the positive result among the five treatments, and T4 got the highest economic return with an increase of 413 USD/ha compared with CK. In 2012, there was a positive economic return for all amendments except for T5, with T3 providing the greatest increase of 795 USD/ha compared with CK. From the three years' cost benefit analysis, the single amendment treatments had a higher economic return than compound amendment treatments, and T5 did not increase economic return, mostly because its high input cost.

Table 3 Cost-Benefit of potato by applying soil amendments in 2010-2012（USD/ha）compared to the control treatment with no soil amendment

Treatment	Input, USD/ha	Output, USD/ha	Increase in output over that for the control treatment, USD/ha
2010			
CK	-	1349	-
T1	181	1655	126
T2	663	1840	-172
T3	217	1703	138
T4	699	2028	-20
T5	482	1488	-343
2011			
CK	-	1446	-
T1	181	1879	252
T2	663	2098	-11
T3	217	2013	349
T4	699	2559	413
T5	482	1601	-327
2012			
CK	-	2373	-
T1	181	3123	569
T2	663	3536	499
T3	217	3386	795
T4	699	3629	556
T5	482	2774	-81

Note : Treatment code: CK, no amendment control; T1, PAA; T2, PAA plus HA; T3, PAM; T4, PAM plus HA; T5, HA.

4 Discussion

Our data showed that soil moisture content was higher in the 0-40 cm layers in plots receiving water holding soil amendments than in control plots where no amendments were applied (Figure 2). The soil amendments retain the limited rainfall and lower evaporation losses (Al-Humaid and Moftah, 2007). A smaller effect in 0-10 cm layer is due to water removal by evapotranspiration. There was consistent ordering of soil moisture content applied with soil amendments at all layers and all years with the compound amendment treatments producing greater effect than the single amendments. The differences among amendments in deep soil (40-100 cm) were much lower than the near surface layers; amendments are incorporated by tillage into the surface layers of the soil and are not present in the deeper layers. Temporal variation of soil moisture content was also increased by soil amendments at all depths to 100 cm in 2011, and to a lesser extent in 2010 and 2012 (Figure 3). This indicates that the effect of the soil amendments which are incorporated by tillage into the top 20 cm layer of soil can affect soil moisture content at much deeper layers. The water holding amendments are effective in increasing the water holding capacity, reducing evaporation losses (Bouranis et al., 1995; Huettermann et al., 2009) in the surface layers and increasing infiltration rates (Sojka et al., 1998; Green et al., 2000; Bjorneberg et al., 2003), which increase soil moisture in the deeper layers. The amendments both improve soil moisture content water in the top soil layers which is available for crop use, and restore soil groundwater in the deeper soil layers during periods of medium rainfall. Hence, under medium rainfall conditions, they can contribute to the sustainability of agricultural crop production in semi-arid areas.

In our experiment, potato fresh tuber yield, commercial tuber proportion and WUE were increased by soil amendments in 2010, 2011, and 2012 (Table 2 and Figure 4), which was consistent with the findings of Dorraji et al. (2010) for corn. Economic return is strongly influenced by both total yield and commercial tuber proportion, as the value of commercial tubers is more than double that for the utility tubers. Soil amendments increased the yield of all of potato fresh tuber, commercial tuber proportion and WUE. Rainfall was the same for all amendments in the given years, and therefore WUE is directly related to yield. Other researchers showed that amendments not only could hold water but also hold plant nutrients releasing them slowly to supply crop growth, hence, they improve both water and fertilizer use efficiency (Bhardwaj et al., 2007). Magalhaes et al. (1987) found that leaching was also reduced as the amendments held nutrients, which reduces environmental contamination of the groundwater providing an added benefit for fragile ecosystems in arid and semi-arid areas. T4 consistently produced the highest fresh tuber yield, commercial tuber proportion, WUE and highest crop value, but because of its high cost, it produced the highest economic return in only one of the three years. Single amendment treatments, T1 and T3 had a higher economic return than the compound amendment treatments (T2 and T4), but the economic return for the single amendment T5 was lower than for the control, CK. Thus, both differences in yield and input costs need to be considered to determine the most profitable system for the farmers. Wide spread adoption of amendment use will likely drive improvements in technology for manufacture of amendments, and together with economy of scale resulting from increasing demand, the cost of amendment production may decrease which would improve the economics for farmers.

The data of soil moisture content, fresh tuber yield and WUE showed compound amendment treatments are better than single amendment treatments. This suggests that an increasing the rate of a single amendment treatment might have the same effect as compound amendment treatments. Synthetic polymers had good interaction with natural soil amendment HA; they had positive effect in plant growth, and improved yield and WUE, this was consistent with Huang et al. (2007). Clearly, more work is required to optimize the amendment rate to achieve maximum benefit and greatest economic return.

Our research indicates that there is an opportunity to improve economic and environmental sustainability of agricultural crop production through the use of water absorbing soil amendments in semi-arid and arid regions. Agricultural development is a high priority of the Chinese government, and developing research and extension programs on soil amendments would contribute to the overall government objectives.

5 Conclusions

In this study, we compared effect of synthetic and natural water absorbing soil amendments on soil moisture, fresh tuber yield, commercial tuber proportion, WUE, and economic return for potato production in semi-arid land in Inner Mongolia. Soil amendments significantly ($P \leq 0.05$) affected soil moisture content except in periods with too much precipitation. The greatest difference in soil moisture content was in the 20-40 cm layer. Soil amendments increased fresh tuber yield, commercial tuber proportion and WUE; T4 with PAM plus HA had the greatest effect. However, T3 with PAM always provided the greatest improvement in economic return.

It would be beneficial to study long-term effect of soil amendments on soil physical, chemical and biological properties to develop a more complete understanding of the long-term effect of water absorbing soil amendments. A more complete understanding would form the basis for development management strategies for improvement of soil water use in crop production in semi-arid areas.

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