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Potato-Cabbage Double Cropping Effect on Nitrate Leaching and Resource-Use Efficiencies in an Irrigated Area*[1]

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ABSTRACT

To reduce the nitrate leaching risk after potato (*Solanum tuberosum* L.) harvest and improve nitrogen fertilizer-use efficiency, a potato-cabbage double cropping system (DCS) was established at Hetao, North China, an arid area with irrigated land. A two-year field experiment demonstrated that planting early-maturing potato cultivar under plastic mulch shortened its growth period by 14 d and allowed a second crop of cabbage to scavenge the soil residual NO_3^--N to a depth of 160 cm, substantially reducing the risk of nitrate leaching into groundwater. The yearly total N uptake in DCS was about 110 kg ha^{-1} more than that in the conventional cropping system (CCS), *i.e.*, mono potato planting. This accounted for apparent nitrogen recovery (ANR) improvement of 16.90%–26.57% in the DCS as compared to that in the CCS for both years. As a result, the soil residual NO_3^--N in the 0–160 cm soil profile in the DCS was lower than that in the CCS. The solar energy-use efficiency and soil-use efficiency were also substantially increased with DCS.

Key Words: apparent nitrogen recovery, nitrogen uptake, soil resources, solar energy, yield

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China ranks highest in potato (*Solanum tuberosum* L.) production in the world with an annual production of 73.28 million metric tons on an area of 5.08 million hectares (Jia *et al.*, 2011). Likewise, China's nitrogen (N) fertilizer consumption became the highest in the world in 1985 and increased to 38% of the world's total N production in 2005 (FAOSTAT, 2006). However, N uptake efficiency in potato production in China, especially in the Hetao irrigated area of Inner Mongolia, is quite low because of the shallow root system of potato and excessive rates of N application (Tanner *et al.*, 1982; Hu *et al.*, 2009). In addition, the local autumn irrigation habit after harvest to keep soil moisture for ensuring young seedlings' emergence next year when the Yellow River is still frozen enhances the nitrate vertical movement in the soil (Feng *et al.*, 2003). Therefore, environmental risk by nitrate leaching from fertilizer and manure is a serious problem. Feng *et al.* (2005) reported about 17.1% of the wells sampled in the Hetao irrigated region showed water NO_3^--N concentrations exceeding the WHO maximum allowable contamination level (10 mg NO_3^--N L^{-1}) throughout the year for public health intervention.

Many reports indicate that residual N remaining in the soil that was not taken up by the former crop can be recovered by growing catch crops (Thorup-Kristensen, 1994, 2001; Vos and van der Putten, 1997; Zhou *et al.*, 2008). The frost-free period in the Hetao potato production region is about 170 d, much longer than the potato growth period. Furthermore, this region has abundant sunlight resources, totalling 3 766.95–4 185.5 MJ m^{-2} during April through September, and thus can support double cropping. Therefore, growing a deep rooted crop after harvesting potato can be an effective strategy to utilize the residual soil N to mitigate the loading of this N to groundwater, and increase solar energy-use efficiency as well as soil-use efficiency.

In order to ensure success of the double crop system, plastic mulch and early-maturing potato cultivars are employed. Plastic mulch has the positive effects of

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regulating soil temperature and thereby advancing the sowing and harvesting dates (Cook *et al.*, 2006; Ghosh *et al.*, 2006; Wang *et al.*, 2009; Hou *et al.*, 2010) to provide sufficient growing season for a catch crop, which in return reduces nitrate leaching (Islam *et al.*, 1994; Bowen and Frey, 2002; Wu *et al.*, 2002; Romic *et al.*, 2003; Haraguchi *et al.*, 2004). With earlier tuber set, the early-maturing potato cultivars exhibit a higher early growth rate than the late-maturing cultivars (Shateriana *et al.*, 2005).

Cruciferous crops, such as cabbage (*Brassica oleracea* L. convar. *capitata* (L.) Alef.), have fast and deep rooting system reaching more than 2 m than that of cereal crops, and are therefore effective in recovering nutrients from deeper soil horizons (Kristensen and Thorup-Kristensen, 2004; Thorup-Kristensen, 2006). Therefore, cabbage was used as a catch crop in this study. The objective of this study was to investigate the feasibility of potato-cabbage double cropping in enhancing efficient utilization of resources including recovery of residual soil nitrate following potato harvest in an irrigated area of North China.

MATERIALS AND METHODS

Study site

A filed experiment was conducted during 2009–2010 at a suburb of Bayannur City, in the Hetao irrigated area, Inner Mongolia Autonomous Region (40° 53′ N, 107° 10′ E, 1 032 m above sea level), North China. It has a temperate continental climate, with mean annual sunshine of > 3 258 h, annual accumulated temperature (> 10 °C) of 3 049 °C, annual frost-free season of 160–180 d. Cumulative precipitation during the growing season was 72 and 135 mm in 2009 and 2010, respectively, with > 70% of the annual precipitation occurring from June to September. In both years, potato followed winter wheat (*Triticum aestivum* L.). The soil at the experimental site was a clay loam soil with an average bulk density of 1.358 g cm^{-3}. The soil chemical properties of the 0–60 cm depth, the potato root zone, are shown in Table I.

TABLE I

Some soil chemical properties of the 0–60 cm depth from the experimental site in the two years studied

Year	Organic matter	Total salt	Total N	Olsen-P	NH_4OAC-K^+	pH
	g kg^{-1}			mg kg^{-1}		
2009	19.8	2.1	1.15	75.7	234	8.1
2010	14.4	0.8	1.03	31.7	121	8.6

The preplanting nitrate residuals of the 0–60 and 60–160 cm soil layers were 73.66 and 41.05 kg ha^{-1}, respectively, in 2009, and 90.09 and 51.63 kg ha^{-1}, respectively, in 2010. For both years, separate experimental blocks were used to avoid N carryover and confounding of treatment effects.

Experimental design

A late-maturing potato cultivar, Kexin No. 1 (K1), was used in the conventional cropping system (CCS). Early-maturing potato cultivar Favorita (F) was chosen in the double cropping system (DCS), and cabbage cultivar Qinbai No. 2 was used as the catch crop in the double cropping system. For both DCS and CCS, triple superphosphate and K_2SO_4 were broadcast and incorporated prior to planting, at the rate of 75 kg P_2O_5 ha^{-1} and 150 kg K_2O ha^{-1}, respectively. Nitrogen was applied at 225 kg N ha^{-1} (489 kg ha^{-1} urea), 50% at planting and 50% top dressed at flowering stage, and a control with no N was also evaluated for both DCS and CCS, resulting in 4 treatments abbreviated as DCS225, CCS225, CCS0, and DCS0. No N was applied to cabbage. A randomized complete block design was used with three replications.

For the double cropping system, before planting at the end of each March, after basal fertilizers were applied, transparent plastic film (PE film) of 0.008 mm thick and 1.5 m wide was placed on the soil surface with the edges buried in the soil. Each plot was composed of rows 12 m in length at 0.5-m spacings. The mother tubers of the early-maturing potato cultivar F were planted at 0.4-m spacings between the plants (*i.e.*, 55 500 seedlings per hectare) on the flat ground, 8–10 cm beneath the film with punches on April 9 of each season. The tubers were harvested on July 10 of each year and the plastic mulches were removed meanwhile. Subsequently, cabbage seeds were sown at 0.6 m × 0.6 m spacings (30 000 seedlings per hectare) one or two days after harvest of the early-maturing potato and harvested in mid October. The cumulative irrigation for potato was 135 mm each year. Cabbage was irrigated 3 times with a total of 435 mm and 4 times with a total of 570 mm in 2009 and 2010, respectively.

For the conventional cropping system, the potato planting system density was similar to that described for the double cropping system. Planting was done on April 25 and harvest at the end of September according to the local farmers' practice. The cumulative irrigation amount was similar to that for potato in DCS.

Soil temperature measurement

From planting through seedling emergence, soil emperature was measured at 10 cm depth at 14:00 everyday using a soil geothermometer (Hongxing Meter, China).

Sampling and analyses

Tubers and vines from 5 potato plants and leaves of 5 cabbage plants were randomly sampled from each plot in both years. All plant materials were washed with tap water and tuber samplings were sliced into 5-mm thick sheets and then oven dried at 80 °C for 60 h until constant weight to record biomass dry weights. Concentration of N in the biomass was measured with modified Kjeldahl method (Bao, 2008). Potato tuber yields and cabbage leaf yields were measured from 3 rows of 12 m length per plot. Whole cabbage biomass was assumed to be accumulated before the end of each September since frost occasionally occurred in early October.

Soil core (20 mm diameter) samples of 0–60 and 60–160 cm depths were taken from five random positions per plot twice, pre-plant and post-harvest, and the samples from the same soil depth were mixed. Concentration of NO_3^--N in the soil samples was measured after KCl (2 mol L^{-1}) extraction using a continuous flowing analyzer (Skalar San^{++}, Netherland).

Calculation

NO_3^--N accumulation in plant (kg N ha^{-1}) was calculated by subtracting the pre-fertilization NO_3^--N residual from the NO_3^--N residual after harvest for the same soil depth. Apparent N recovery (ANR) was estimated as follows:

$$\text{ANR (\%)} = [(\text{N uptake in fertilized treatments} - \text{N uptake in unfertilized treatments})/\text{amount of N fertilizer applied}] \times 100 \quad (1)$$

Solar energy-use efficiency (EUE) was calculated using the formula:

$$\text{EUE (\%)} = \frac{\Delta W \times H}{\Sigma s} \times 100 \quad (2)$$

where ΔW is the plant biomass increment during the planting season (g m^{-2}); H is the energy content per gram dry matter (kJ g^{-1}) and the average energy content in the carbohydrate (17.2 kJ g^{-1}) was utilized; Σs is the solar energy aggregate value from April to September in Bayannur City, 3 976 MJ m^{-2} (Meteorological Bureau of Bayannur City).

The land equivalent ratio (LER) was introduced for calculating soil-use efficiency as follows:

$$\text{LER} = \sum_{i=1}^{n}(Y_i/Y_i') = Y_1/Y_1' + Y_2/Y_2' + \cdots + Y_i/Y_i' \quad (3)$$

where Y_i is the crop yield per unit area (kg hm^{-2}) under the double cropping system; Y_i' is the crop yield per unit area (kg hm^{-2}) under the mono cropping system; and i is a specific crop under the double cropping. There was no unit for LER (Liu and Zhang, 2006).

Statistical analysis

The significance of difference between the double cropping system and the conventional cropping system with respect to all response indicators was tested by analysis of variance (ANOVA). The means were separated by Tukey's test at 5% (SAS Institute Inc., USA).

RESULTS AND DISCUSSION

Potato seedling emergence

During the potato seedling emergence periods of 2009 and 2010, 10-cm depth soil temperatures were 2.6–4.9 and 1.6–5.2 °C greater with mulch than without mulch (Fig. 1). As a result, emergence was at least 12 d earlier in DCS than CCS in both years (Table II) due to maximum utilization of greater solar radiation in DCS in the early growing season. Average solar radiation in May both years was 811 MJ m^{-2}, which was the highest among all months.

TABLE II

Seedling periods for the double and conventional cropping systems with or without N application in the two years studied

Treatment[a)]	2009		2010	
	Planting date	≥ 90% emergence date	Planting date	≥ 90% emergence date
DCS0	April 9	May 20	April 9	May 24
CCS0	April 25	June 5	April 25	June 7
DCS225	April 9	May 20	April 9	May 24
CCS225	April 25	June 5	April 25	June 7

[a)] DCS0 and CCS0 are the treatments without N application for the double and conventional cropping systems, respectively, and DCS225 and CCS225 are the treatments with N application of 225 kg N kg^{-1} for the double and conventional cropping systems, respectively.

The seedling emergence period of 2010 showed 3 d of < 10 °C soil temperature in both mulched and unmulched soils. In 2009, however, soil temperature with mulch was > 12 °C for this period. Men and Liu (1995)

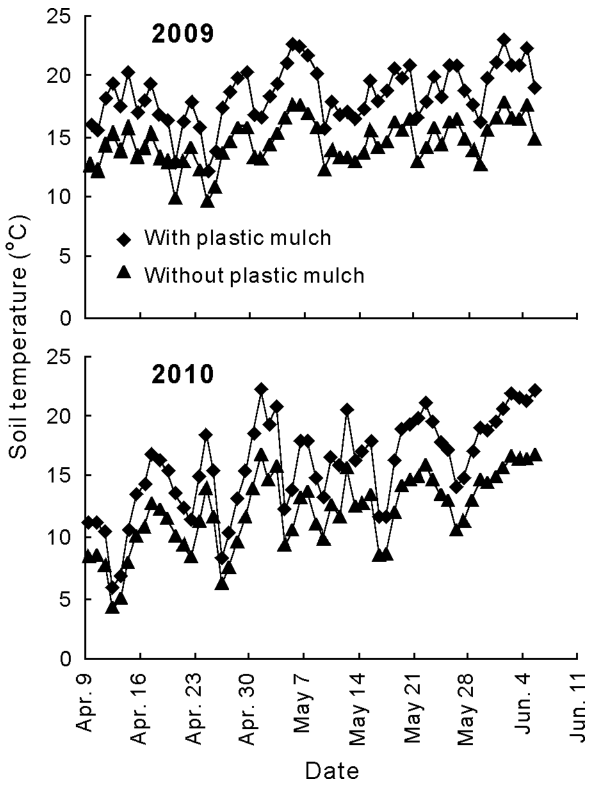

Fig. 1 10-cm depth soil temperatures with or without plastic mulch at 14:00 daily in 2009 and 2010 during the potato emergence period.

reported that potato has the fast growth of roots and sprouts at 10–12 °C. No emergence difference was shown among the different N treatments for both potato cultivars, which was explained by sufficient nutrients in the mother tubers used.

N uptake and ANR

The ANR with DCS was 26.57% and 16.90% greater than that with CCS in 2009 and 2010, respectively (Table III). This demonstrated that high N recycling could be achieved by growing a catch crop.

The N uptake by the early-maturing potato cultivar Favorita used in DCS was significantly lower than that by the late-maturing K1 used in CCS in both years across both treatments (Table III). However, the cumulative N uptake by potato and cabbage in the DCS225 treatment was 109.6–110.7 kg ha^{-1} greater than that in the CCS225 treatment across both years. Total N uptake in the DCS0 treatment was similar to that of the CCS225 treatment in 2009, and was 17.55 kg ha^{-1} greater than that of the CCS225 treatment in 2010. The N uptake by cabbage was significantly higher than that by potato in both DCS225 and DCS0 treatments in 2009 and 2010. These results suggested that the cabbage crop following potato played a pivotal role for recovery of soil residual N. Our results combined with a previous report that cabbage crop could accumulate 300–330 kg N ha^{-1} with a yield of 167 Mg ha^{-1} (Li *et al.*, 2003) implied that the vast cabbage biomass accumulation was dependent up the large amount N uptake.

NO_3^--N apparent accumulation

The apparent NO_3^--N accumulation at each soil depth was significantly greater for the CCS225 treatment as compared to the DCS225 treatment (Table IV). This was a clear indication of the ability of cabbage crop to scavenge NO_3^--N from the soil in the 0–60 and 60–160 cm depths following the potato crop. Kristensen and Thorup-Kristensen (2004) and Thorup-Kristensen (2006) reported that cabbage can take up NO_3^--N from the soil below 1 m. A planting combination of early-maturing potato cultivar with cabbage can reduce the risk of nitrate leaching as compared to

TABLE III

N uptake and apparent N recovery (ANR) for the double and conventional cropping systems with or without N application in the two years studied

Treatment[a)]	2009				2010			
	N uptake			ANR	N uptake			ANR
	Potato	Cabbage	Total		Potato	Cabbage	Total	
	kg ha^{-1}			%	kg ha^{-1}			%
DCS0	42.79 d[b)]B[c)]	81.84 bA	124.63 b	–	46.06 cB	106.95 bA	153.01 b	–
CCS0	74.78 c	–	74.78 c	–	80.40 b	–	80.40 d	–
DCS225	89.46 bB	143.48 aA	232.93 a	48.14 a	81.20 bB	164.92 aA	246.12 a	41.38 a
CCS225	123.32 a	–	123.32 b	21.57 b	135.46 a	–	135.46 c	24.48 b

a)DCS0 and CCS0 are the treatments without N application for the double and conventional cropping systems, respectively, and DCS225 and CCS225 are the treatments with N application of 225 kg N kg^{-1} for the double and conventional cropping systems, respectively.

b)Means followed by the same lowercase letter in the same column are not significantly different at $P < 0.05$.

c)Means followed by the same uppercase letter in the same row of the same year are not significantly different at $P < 0.05$.

TABLE IV

Apparent NO_3^--N accumulation in the soil at different depths with the double and conventional cropping systems with N application in the two years studied

Treatment[a)]	0–60 cm depth		60–160 cm depth	
	2009	2010	2009	2010
	kg N ha^{-1}			
DCS225	−15.78 b[b)]	−33.41 b	−7.76 b	−15.21 b
CCS225	29.31 a	16.68 a	17.53 a	7.43 a

a)DCS225 and CCS225 are the treatments with N application of 225 kg N kg^{-1} for the double and conventional cropping systems, respectively.
b)Means followed by the same letter in the same column are not significantly different at $P < 0.05$.

the conventional potato planting, *i.e.*, single cropping of late-maturing potato cultivar.

Solar energy-use efficiency and soil-use efficiency

The solar energy-use efficiency of the DCS was significantly greater than that of the CCS in both years with or without N applied (Table V). Sunlight is the main energy resource for photosynthesis to produce carbohydrate. The average solar energy-use efficiency for a high yielding grain crop is about 1%–2%, while the value for a vegetable crop is even lower (Wang, 2009). Improving the solar energy-use efficiency is the key to improve the yield. Some studies have suggested that increased planting density and adoption of intercropping are effective strategies for improving solar energy-use efficiency (Huang, 1999; Li *et al.*, 2005). Our results showed that the early-maturing potato cultivar under plastic mulch enabled double cropping in the Hetao irrigated area, and therefore enhanced the solar energy-use efficiency as compared to the mono potato planting.

TABLE V

Solar energy-use efficiency and soil-use efficiency with the double and conventional cropping systems with or without N application in the two years studied

Treatment[a)]	Solar energy		Soil	
	2009	2010	2009	2010
	%			
DCS0	0.43 b[b)]	0.50 b	–	–
CCS0	0.29 c	0.31 d	–	–
DCS225	0.71 a	0.72 a	1.88	1.84
CCS225	0.45 b	0.47 c	1.00	1.00

a)DCS0 and CCS0 are the treatments without N application for the double and conventional cropping systems, respectively, and DCS225 and CCS225 are the treatments with N application of 225 kg N kg^{-1} for the double and conventional cropping systems, respectively.
b)Means followed by the same letter in the same column are not significantly different at $P < 0.05$.

The soil-use efficiency was also greater in the DCS225 treatment as compared to the CCS225 treatment in both years (Table V). Rapid urbanization in China is resulting in a reduction in cultivated land resource, while the demand for food is increasing. Therefore, strategies to increase soil-use efficiency in Chinese agriculture are of major priority to meet the abovementioned conflicting demands.

Crop yields

The yields of potato and cabbage were greater with 225 kg ha^{-1} N application as compared to those without N application in both years (Table VI). Potato yields were similar across both CCS and DCS systems without N application, but were greater with the former as compared to those of the latter with 225 kg ha^{-1} N application in both years.

TABLE VI

Yields of potato and cabbage (fresh weight) under the double and conventional cropping systems with or without N application in the two years studied

Treatment[a)]	2009		2010	
	Potato	Cabbage	Potato	Cabbage
	Mg ha^{-1}			
DCS0	21.01 c[b)]	88.92 b	22.13 c	108.74 b
CCS0	21.93 c		22.84 c	
DCS225	29.96 b	137.94 a	29.10 b	154.03 a
CCS225	33.91 a		34.76 a	

a)DCS0 and CCS0 are the treatments without N application for the double and conventional cropping systems, respectively, and DCS225 and CCS225 are the treatments with N application of 225 kg N kg^{-1} for the double and conventional cropping systems, respectively.
b)Means followed by the same letter in the same column are not significantly different at $P < 0.05$.

CONCLUSIONS

The potato-cabbage double cropping system adopted in this study with an early-maturing potato cultivar planted under plastic mulch facilitated 14 d earlier emergence of seedlings as compared to the conventional cropping system. As a result, the complete growth of the second crop of cabbage was possible before the onset of freezing frost. The N uptake by the early-maturing potato cultivar Favorita used in the double cropping system was lower than that by the late-maturing cultivar Kexin No. 1 used in the conventional cropping system. However, yearly total N uptake by both potato and cabbage in the double cropping system was greater than that in the conventional cropping system, thus contributing to higher apparent nitrogen recovery in the double cropping system in both years. The residual soil NO_3^--N down to the 160 cm depth at the end of the growing season was greater in the conventional cropping system than the double cropping system. Therefore, this study demonstrated that cabbage following potato was an effective cropping system to scavenge residual soil NO_3^--N from the soil and thus reduce the risk of NO_3^--N leaching and loading into groundwater. Furthermore, the double cropping system enhanced solar energy- and soil-use efficiency as well.

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