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ORIGINAL ARTICLE

Fertigation combined with catch crop maximize vegetable yield and minimize N and P surplus

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Abstract Excessive fertilization is a common agricultural practice that often results in high risk of nitrogen (N) and phosphorus (P) losses in vegetable production in China. To reduce these losses, it is crucial to control residual nutrient levels in the rootzone and maintain crop growth. A 3-year field experiment was therefore conducted to investigate the effects of optimal fertigation (OF), OF combined with summer catch crop (OF-SCC; sweet corn with residue incorporation after harvest) or wheat straw application (OF-WSA; soil amended with wheat straw before cucumber seedling transplanting) on soil nutrients, soil residual N and P levels in the rootzone. The conventional management (flood irrigation with excessive fertilization and bare fallow during the summer period) served as control. The results showed that, although OF reduced irrigation amount, N input and P input by 49, 50 and 53%, respectively, it did not affect N and P uptake and fruit yields, and significantly reduced N and P surplus in the rootzone by 60 and 59%, respectively, when compared to the control. The SCC extracted 72–74 kg N ha^{-1} $year^{-1}$ and 10–13 kg P ha^{-1} $year^{-1}$ from soils. In addition, SCC and WSA increased soil soluble organic N in the rootzone but had little influence on N and P surplus. Generally, OF was efficient in reducing soil residual N and P, while SCC could temporarily retarded N leaching and improved nutrient recycling in the rootzone. Our results infer that OF combined with SCC is an efficient method for reducing soil N and P losses.

Keywords Fertigation · Summer catch crop · Straw application · Soil nutrients · Vegetable growth

Lingyun Kang and Bingqian Fan have contributed equally to this study and share first authorship.

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Introduction

China has developed 5.35 million ha of protected fields mainly used to produce vegetables (Chen et al. 2013; NBS 2015). These protected fields are usually suitable for vegetable growth and can maintain relatively stable yields, based on double cropping systems with bare fallow during the summer period. However, excessive fertilization and irrigation, which far exceed the nutrient and water requirements of crop plants, are two common agricultural practices in Chinese greenhouse fields (Yu et al. 2010; Liang et al. 2013, 2015; Yang et al. 2016). Conventionally, farmers applied large amount of animal manure as base fertilizer and flushed excessive water-soluble

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fertilizers as dressing fertilizer using flood irrigation (Zhu et al. 2005). These conventional practices have resulted in serious nitrogen (N) losses through leaching and high phosphorus (P) surplus in soils (MacDonald et al. 2011; Yan et al. 2013). For instance, Ju et al. (2006) reported that more than 1000 kg nitrate–N ha^{-1} was annually leached into a depth of 0.9–1.8 m in a greenhouse field system in the North China Plain. Yan et al. (2013) summarized that the gross over-fertilization occurred in Chinese greenhouse fields were 571 kg P ha^{-1} per cropping season and that for most soils the Olsen-P exceeded the critical level (46–58 mg P kg^{-1}) for vegetable production. Since excessive fertilization has resulted in serious environmental risks, it is critical to reduce nutrient losses to the environment by limiting the soil residual N and P levels in the rootzone, without influencing crop yields.

Over the past two decades, adequate fertilizer use has been recognized as an efficient method to control soil residual N and P levels in the rootzone and to maintain nutrient in levels that are critical for crop growth (Hartz et al. 2000; Breschini and Hartz 2002). Since ammonium is often rapidly converted into nitrate–N in soils and nitrate-N can be easily leached into ground water (Demurtas et al. 2016), most studies have investigated the effect of reduced N fertilization and related irrigation strategies on rootzone soil N and crop growth in greenhouse fields (Zhu et al. 2005; Ren 2011; Fan et al. 2014). For example, Ren (2011) used in-season N management tools to balance N input and output in the rootzone, and reduced N application rate by 40% during the N side dressing period. However, it was still a challenge to reduce N losses through the fertilizer recommendation, since high manure application as base fertilization still led to high residual N in soils during summer fallow season due to high N mineralization (Ju et al. 2007; Watts et al. 2010). Furthermore, P recommendation based on "build-up and maintenance approach" was inefficient in controlling residual P level in excessively fertilized soils, because of high P application rate but low P removal by vegetable plants (Yan et al. 2013; Annaheim et al. 2015). Thus, in addition to adequate fertilizer recommendation, there is an urgent need to take measures to reduce nutrient losses during cropping seasons and the summer fallow period.

Since greenhouse vegetable fields are generally characterized by rapid growth rates but poor root systems, frequent irrigation and fertilization are needed to achieve high yields (Mayfield et al. 2002). To meet this need, several optimal fertigation techniques have been developed to manage rootzone nutrients (Incrocci et al. 2017; Thompson et al. 2017). For example, Liang et al. (2014) found that based on fertilizer-N recommendation, optimal daily fertigation could maintain relatively stable mineral N levels and reduce N losses in the rootzone. Fan et al. (2014) demonstrated that optimal fertigation could decline nitrate-N leaching by 93%, when compared to conventional practices. Although optimal fertigation can efficiently reduce nutrient losses through precise irrigation control during the crop growth period (Strock et al. 2004; He et al. 2007), it is difficult to prevent nutrient leaching during the summer fallow period because of the summer intensive heavy rainfall.

Planting catch crops with deep root system and high nutrient uptake capacity during the summer fallow period was considered to mitigate nutrient loss and recover residual soil nutrients in deep soil layers (Min et al. 2011; Guo et al. 2018). Furthermore, catch crop residues can be incorporated into soils, which may improve soil nutrient recycling and enhance soil nutrient availability. More importantly, catch crop residue can increase labile organic matter in soils and promote the transformation of inorganic nutrients to organic forms (Piotrowska and Wilczewski 2012), leading to lower leaching losses of nutrients (Tian et al. 2011). For example, as an important pool of the total N budget, soluble organic N comprises 28–44% of the total soluble N in greenhouse field soils (Liang et al. 2015). To date, however, little information is available regarding the influence of summer catch crop and residue incorporation on soluble organic nutrients.

In this study, we conducted a 3-year field experiment with six succeeding cropping seasons for cucumber and tomato production. The objectives of this research were to (1) investigate the effects of optimal fertigation, summer catch crop and straw application on the surplus and accumulation of N and P, the residual N and P levels in the rootzone and crop growth, and to (2) evaluate the efficiency of these agricultural practices in reducing soil N and P losses in the rootzone.

Materials and methods

Experimental site

The study was conducted in a greenhouse field site (39.72°N, 115.98°E), located in a semi-humid temperate region with a mild climate and four distinct seasons, in Fangshan, Beijing, China from 2011 to 2013. The annual average temperature ranged from 8 to 12 °C with a monthly mean maximum of 31 °C in July and a monthly mean minimum of − 9 °C in January. The frost-free period was about 180–200 days from mid-April to late-October. The average annual rainfall was approximately 600–700 mm, with a monthly mean maximum of 179 mm in July and a monthly mean minimum of 2 mm in December.

The experiment was conducted in a commercial greenhouse field with a back wall constructed of clay and a curved roof covered with polyethylene film. The greenhouse field had a north–south orientation (61 m × 5.2 m) and was typically constructed in a suburban region in 2010. Soil temperature and moisture were monitored at a depth of 5 cm every 10 min with automatic-sensors (AR5, AVALON) (Fig. 1). The soil texture, physiochemical properties of greenhouse field soils (0–90 cm) before the experiment were presented in Table 1.

Crop planting

Cucumber (*Cucumis sativus* L. cv. Zhongnong No. 26) and tomato (*Lycopersicum esculentum* Mill. cv. Tiaozhanzhe) plants were grown during the first five and the last cropping seasons, respectively. The winter–spring (WS) season, summer fallow (SF) period and autumn–winter (AW) season were from mid-March to late-June, from late-June to early September and from early-September to the next early-January, respectively.

Cucumber seedlings were transplanted by hand and planted in double rows at a density of 47,600 plants ha^{-1} on March 11, 2011, March 4, 2012 and March 15, 2013 in the WS season, and on September 5, 2011 and September 10, 2012 in the AW season, respectively. Tomato seedlings were transplanted at a density of 50,000 plants ha^{-1} on September 16, 2013. The plants residues were removed from the greenhouse field at the final harvest (June 29, 2011, June 28, 2012 and June 27, 2013 for the WS season; January 13, 2012, January 10, 2013 and March 6, 2014 for the AW season). At the beginning of the summer fallow period, sweet corn seedlings with three leaves were transplanted by hand with 0.6 m row spacing and 0.3 m plant spacing on June 30 from 2011 to 2013 and harvested on September 1, 2011, September 6, 2012 and September 10, 2013, respectively.

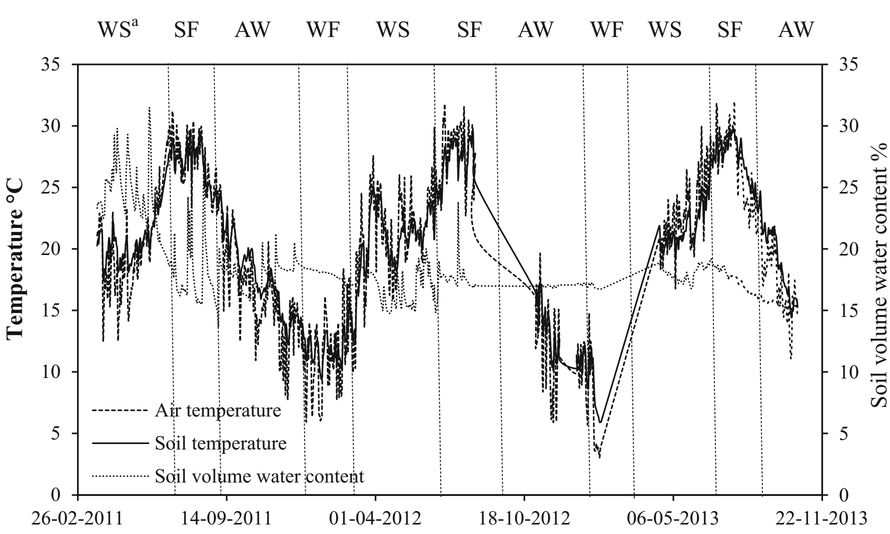

Fig. 1 Soil temperature and soil water content (5 cm depth) in a greenhouse vegetable field in Fangshan, Beijing from 2011 to 2013. [a]*WS* winter–spring season, *SF* summer fallow period, *AW* autumn–winter season, *WF* winter fallow period

Table 1 Soil texture, physical and chemical properties at different soil layers at initial stage of the experiment in a greenhouse vegetable field in Fangshan, Beijing in 2010.12.23

Parameters	Unites	Soil layer (cm)		
		0–30	30–60	60–90
Soil texture[a]		Loam	Silt loam	Silt loam
Sand content	%	36	28	31
Silt content	%	48	55	51
Clay content	%	16	17	18
Soil moisture content	%	23.8	19.6	20.8
Soil bulk density	g cm^{-3}	1.42	1.45	1.44
Total N	g kg^{-1}	1.80	1.22	0.89
NO_3^-–N	mg kg^{-1}	148.3	33.1	30.0
NH_4^+–N	mg kg^{-1}	1.9	0.9	0.5
Organic matter	g kg^{-1}	20.3	13.0	8.7
Olsen-P	mg kg^{-1}	189.4	18.3	6.6
Available K	mg kg^{-1}	237	77	85
Soil pH (w/s = 2.5:1)		7.03	7.52	7.22
EC (w/s = 5:1)	ms cm^{-1}	1.22	0.30	0.28

[a]According to the USDA's soil texture classification system

Experimental design

The treatments included (1) conventional flood irrigation with excessive fertilization (Control), (2) Optimal fertigation (OF), (3) OF combined with wheat straw application (OF-WSA): soil amended with wheat straw before cucumber seedling transplanting and (4) OF combined with summer catch crop (OF-SCC): sweet corn with residue incorporation after harvest. The experiment was a randomized block design with three replicates and the size of each replicate plot was 18.72 m^2 (5.2 m × 3.6 m).

A basal organic fertilizer was broadcast and incorporated into the 0–20 cm soil via rotary tillage before seedling transplanting. Pig manure was used as the basal fertilizer in the 2011 WS season, and composted manure with mushroom waste was used for the other seasons. Urea, monophosphate and potassium sulphate were used as dressing fertilizer N, P and K, respectively. Drip irrigation was applied in the OF, OF-WSA and OF-SCC treatments, except for furrow irrigation during seedling transplanting. One vacuum gauge tensiometer was installed at 20-cm soil depth in each subplot and irrigation was commenced when the reading value of tensiometer exceeded the threshold (– 25 kPa). Under the OF, OF-WSA and OF-SCC treatments, plants were fertigated at the intervals of 3–10 days depending on the soil water tension. Under the control, furrow irrigation and fertilization were conducted based on conventional practices. The fertilization and irrigation rates for all treatments were shown in Tables 2 and 3.

Sampling and analysis

Vegetable fruits were picked by hand in each plot and weighed during each harvest event. The cucumber or tomato vines, including the leaf and stem, were collected from each plot at the end of the final harvest and dried at 105 °C for 30 min, then at 75 °C to constant weight for measurement of N, P and K contents using the Kjeldahl method, vanadium molybdate yellow colorimetric method and flame photometry after digestion with H_2SO_4–H_2O_2 (Thomas et al. 1967), respectively. The N, P and K uptakes of aboveground parts were calculated as the sum of the N, P and K uptake in the leaves, stems and fruits.

Composite soil samples were obtained by mixing four soil cores from each plot and collected from 0, 0.3, 0.6, 0.9, 1.2, 1.5 and 1.8 m to measure soluble inorganic (SIN) and organic N (SON) after uprooting of the plants in March, 2014 after six growing seasons. After sieving the soil through a 2 mm sieve, the fresh subsamples were extracted with 1 M KCl at a ratio of 1:10 (dry soil: solution) for 1 h. The SIN (NH_4^+–N and NO_3^-–N) was determined using a continuous flow analyser (AA3, Bran + Luebbe, Germany). The soluble total N (STN) in the filtrate was measured by

Table 2 Nitrogen, phosphorus and potassium input in a greenhouse vegetable field with catch crop and straw incorporation in Fangshan, Beijing from 2011 to 2013 (kg ha^{-1})

Treatment	Fertilizer	2011						2012						2013					
		WS[b]			AW			WS			AW			WS			AW		
		N	P	K	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K
Control[a]	Organic fertiliser	940[c]	405	500	780	131	528	696	131	528	816	128	986	482	93	799	908	406	831
	Inorganic fertilizer	382	167	317	429	76	259	462	83	279	297	65	247	297	65	247	340	59	141
	Total	1323	572	818	1209	208	787	1158	214	807	1113	194	1233	779	157	1046	1248	466	972
OF	Organic fertiliser	470	203	251	390	66	264	348	66	264	408	64	493	214	41	355	413	185	378
	Inorganic fertilizer	278	85	281	216	49	204	194	35	206	135	22	146	122	15	152	216	26	269
	Total	748	288	531	606	114	468	542	101	470	543	86	639	336	56	507	629	211	647
OF-WSA	Organic fertiliser	499	218	283	425	83	298	374	82	293	439	80	524	240	55	383	444	200	411
	Inorganic fertilizer	278	85	281	216	49	204	194	35	206	135	22	146	122	15	152	216	26	269
	Total	777	303	564	641	131	502	568	117	499	574	102	670	362	70	535	660	226	680
OF-SCC	Organic fertiliser	470	203	251	390	66	264	348	66	264	408	64	493	214	41	355	413	185	378
	Inorganic fertilizer	278	85	281	216	49	204	194	35	206	135	22	146	122	15	152	216	26	269
	Total	748	288	531	606	114	468	542	101	470	543	86	639	336	56	507	629	211	647

[a] *Control*: conventional flood irrigation with excessive fertilization, *OF* Optimal fertigation, *OF-WSA* OF combined with wheat straw application (soil amended with wheat straw before cucumber seedling transplanting), *OF-SCC* OF combined with summer catch crop (sweet corn with residue incorporation after harvest)

[b] *WS* winter–spring season, *AW* autumn–winter season

[c] The nutrient contents of organic fertilizers showed as below: 2011WS: N 2.09%, P 0.90%, K 1.11%; 2011AW: N 1.30%, P 0.24%, K 1.05%; 2012WS: N 1.16%, P 0.22%, K 0.88%; 2012AW: N 1.36%, P 0.21%, K 1.64%; 2013WS: N 1.07%, P 0.20%, K 1.78%; 2013AW: N 1.65%, P 0.74%, K 1.51%

Table 3 Irrigation rates in a greenhouse vegetable field with catch crop and straw incorporation in Fangshan, Beijing from 2011 to 2013 (mm)

Year	Season	Control[a]	OF, OF-WSA, OF-SCC
2011	Winter–spring	512	252
	Autumn–winter	180	135
	Total	692	387
2012	Winter–spring	472	214
	Autumn–winter	248	98
	Total	720	312
2013	Winter–spring	345	175
	Autumn–winter	152	100
	Total	497	275

[a]Furrow irrigation was used in Control treatment and drip irrigation was used in OF, OF-WSA, OF-SCC treatments

dual-wavelength (220 and 275 nm) ultraviolet spectrophotometry after alkaline persulfate oxidation (Norman et al. 1985). The SON was determined as the difference between STN and SIN. Soil total N was tested using Kjeldahl method after air dried and through a 0.25 mm sieve (Thomas et al. 1967). The soil organic matter was determined using the potassium dichromate oxidation method (Bao 2010). The Olsen-P and $CaCl_2$-P in the soil were measured by the ascorbic acid method with 0.5 M $NaHCO_3$ (soil/solution ratio of 1:20) and 0.01 M $CaCl_2$ (soil/solution ratio of 1:5), respectively (Olsen et al. 1954; Schofield 1955). Soil degree of P saturation (DPS) was calculated as follows:

$$\mathrm{DPS} = \mathrm{P_{M3}}/(0.039\mathrm{Ca_{M3}} + 0.462\mathrm{Mg_{M3}}) \times 100\%$$

in which, P_{M3}, Ca_{M3}, and Mg_{M3} were concentrations of P, Ca, and Mg extracted from soils using Mehlich 3-extracting solution (0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.015 M NH_4F + 0.13 M HNO_3 + 0.001 M EDTA) by shaking for 5 min at a 1:10 soil to solution ratio. All elements were determined using inductively coupled plasma optical emission spectroscopy (ICP-OES).

Statistical analysis

An analysis of variance was used to determine the statistical significance of the treatment effects. The experiment was analysed as a randomized complete block design. Multiple comparison of mean values was performed using the Fisher's Least Significant Difference (LSD) test at the 0.05 probability level. Analyses were performed using the SAS software package, version 8.0 (SAS Institute Inc., Cary, NC).

Results

Fruit yield, catch crop biomass and nutrient uptake by plants

The fruit yields were significantly lower in the AW (39–45 t ha^{-1} $year^{-1}$) than WS (111–116 t ha^{-1} $year^{-1}$) season due to the lower temperatures in the AW season (Fig. 2). There was no significant difference in fruit yield between the control and the OF-related treatments (OF, OF-WSA and OF-SCC) (Fig. 2), despite significantly reduced water and nutrient inputs under OF-related treatments (Tables 2, 3). The mean annual N and P removal by major crop (cucumber/tomato) uptake were 379–407 and 63–69 kg ha^{-1}, respectively, and accounted only for 18–35% of N input and 11–24% of P input by fertilization (Table 4), indicating the relatively low fertilizer use efficiency in greenhouse vegetable production systems.

The N and P surplus in the rootzone were significantly lower under the OF-related treatments (740–815 kg N ha^{-1} and 218–251 kg P ha^{-1}) than under the control (1869 kg N ha^{-1} and 533 kg P ha^{-1}) (Table 4), because of obviously lower annual N and P inputs by fertilization under the OF-related treatments (1135–1194 kg N ha^{-1} and 285–316 kg P ha^{-1}) compared to the control (2277 kg N ha^{-1} and 602 kg P ha^{-1}) (Table 2).

Sweet corn shoot annually absorbed 72–74 kg N ha^{-1} and 10–13 kg P ha^{-1} from soils in summer, leading to relatively low N and P surplus under the OF-SCC treatment after summer fallow season. For the OF-WSA treatment, 59 kg N ha^{-1} and 31 kg P ha^{-1} were added into soils annually due to wheat straw application.

Soil organic C and residual N

Compared to the control, both the OF-SCC and OF-WSA treatments significantly increased soil organic matter, but did not statistically influence soil total N at

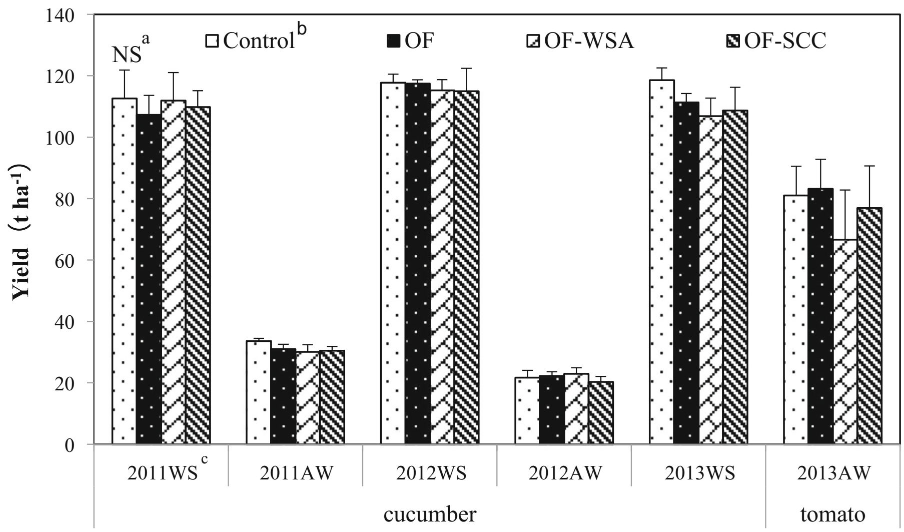

Fig. 2 Fruit yield influenced by catch crop and straw incorporation in a greenhouse vegetable field in Fangshan, Beijing from 2011 to 2013 (t ha^{-1}). [a]The NS means no significant difference for different treatments in the same growing season ($P < 0.05$). [b]*Control* conventional flood irrigation with excessive fertilization; *OF* Optimal fertigation, *OF-WSA* OF combined with wheat straw application (soil amended with wheat straw before cucumber seedling transplanting), *OF-SCC* OF combined with summer catch crop (sweet corn with residue incorporation after harvest). [c]*WS* winter–spring season, *AW* autumn–winter season

the 0–0.3 m depth, resulting in relatively higher soil C/N ratio in the rootzone (Table 5). In addition, the OF treatment did not influence both organic matter and total N in the 0–0.3 m soil.

Generally, for each soil depth (0–0.6, 0.6–1.2 and 1.2–1.8 m), the highest cumulative SON was found under the OF-SCC treatment, followed by the control, OF-WSA and OF treatments (Fig. 3). In particular, cumulative SON in the 0–1.8 m soil was significantly increased by 14.3% by the OF-SCC treatment, but decreased by 11.4 and 36.3% by the OF-WSA and OF treatments, respectively. Moreover, compared to the control, the OF, OF-WSA and OF-SCC treatments significantly increased the proportion of SON in STN in the 0–0.6 m soil by 2.8, 3.5 and 8.6%, respectively (Fig. 3).

Soil available P and degree of P saturation

After six cropping seasons, the Olsen-P of control, OF, OF-SCC and OF-WSA treatments were 259, 204, 168 and 207 mg kg^{-1} in the 0–0.3 m soil, respectively, and were significantly decreased to 7–34 mg kg^{-1} in the 0.3–0.9 m soil (Fig. 4). However, there was no significant difference between each treatment. In addition to Olsen-P, $CaCl_2$-P and degree of P saturation (DPS) were also investigated. Overall, no significant difference in $CaCl_2$-P was observed between the control and the OF and OF-SCC treatments. However, a significantly lower $CaCl_2$-P in the 0–0.3 m soil was found under the OF-WSA treatment compared to the control. The DPS generally showed significant lower values (90–119%) under the OF-related treatments than the control (165%).

Discussion

Effect of optimal fertigation on soil N and P in the rootzone

Although optimal fertigation obviously decreased irrigation amount and N and P inputs compared to conventional management (Table 2), the fruit yields were not reduced during all six cropping seasons (Fig. 2). This result demonstrated that the excessive fertilization and irrigation have no benefit on cucumber/tomato production. It had been demonstrated that, based on fertilizer recommendation, the excessive fertilization could be reduced effectively without yield loss (Ju et al. 2006; He et al. 2007). However, it is still a challenge to reduce potential environmental risk

Table 4 Nitrogen, phosphorus and potassium surplus in a greenhouse vegetable field with catch crop and straw incorporation in Fangshan, Beijing from 2011–2013 (kg ha^{-1})

Growing season	Treatment	Nutrient input			Crop removal			Nutrient surplus[a]		
		N	P	K	N	P	K	N	P	K
2011WS	Control	1323	571	818	213	43	299	1110a[b]	528a	519a
	OF	748	287	531	199	40	277	549c	248c	254c
	OF-WSA	777	302	564	208	41	290	569b	261b	274b
	OF-SCC	748	287	531	203	41	282	545c	247c	249c
2011AW	Control	1209	207	787	108	23	161	1101a	184a	626a
	OF	606	114	468	99	21	149	507c	93c	319c
	OF-WSA	641	131	502	96	20	144	545b	110b	358b
	OF-SCC	606	114	468	98	20	146	508c	93c	322c
2012WS	Control	1158	213	807	221	44	309	937a	169a	498a
	OF	542	101	470	214	43	298	328c	58c	172c
	OF-WSA	568	117	499	213	43	296	355b	74b	203b
	OF-SCC	542	101	470	211	42	293	331c	59c	177c
2012AW	Control	1113	193	1232	258	24	126	855a	169a	1106a
	OF	543	86	639	248	21	135	295c	65c	504c
	OF-WSA	574	102	670	240	22	141	334b	80b	528b
	OF-SCC	546	86	642	237	17	123	309c	69c	519c
2013WS	Control	779	157	1046	202	46	319	577a	111a	727a
	OF	336	56	507	190	44	299	146c	11c	208c
	OF-WSA	362	70	535	182	41	289	180b	29b	247b
	OF-SCC	336	56	507	183	42	288	153c	14c	219c
2013AW	Control	1248	465	972	219	28	241	1028a	437a	731a
	OF	629	210	647	234	31	262	395c	179c	385c
	OF-WSA	660	225	680	198	28	226	462b	197b	454b
	OF-SCC	629	210	647	218	29	245	410c	181c	401c
Annually	Control	2277	602	1887	407	69	485	1869a	533a	1402a
	OF	1135	285	1087	395	67	474	740c	218c	614c
	OF-WSA	1194	316	1150	379	65	462	815b	251b	688b
	OF-SCC	1135	285	1087	383	63	459	751c	221c	628c

[a] Nitrogen, phosphorus and potassium surplus was the difference between the amount of nutrient input and crop removal

[b] The different letter in the same column means significant difference for different treatments in same growing season ($P < 0.05$)

induced by nutrient losses in excessively fertilized soils due to high inputs of basal organic fertilizers (Yan et al. 2013) and high nutrient mineralization and leaching in the summer fallow period (Guo et al. 2008).

Actually, in addition to the recommended amount of fertilizer, the critical levels of water and nutrient supply in the rootzone, which were usually neglected, should be considered in the fertigation recommendation. Under conventional management, flood irrigation may lead to as high as 70% of irrigated water losses through leaching, accompanied by serious nutrient leaching (Guo et al. 2004; Ju et al. 2006; Yu et al. 2005; Yang et al. 2016) and high potential environmental risk such as nitrate contamination in groundwater (Song et al. 2009). However, these negative effects can be reversed through optimal fertigation based on the “6R” rule (right source, right rate,right time,right place,right water and right soil environment) (Hebbar et al. 2004; Tanaskovik et al. 2011). Optimal fertigation can precisely regulate water and nutrient supply due to the reduction of percolation and evaporation, and finally improve fertilizer use efficiency, especially for N and P. Usually, N and P have lower use efficiency than other macronutrient elements, mainly because of high ammonia volatilization, nitrate leaching and P adsorption/fixation by soils (Kruse et al. 2015; Kalkhajeh et al. 2017). In this study, the OF-related treatments had significantly lower N input (Table 2) but did not

Table 5 Total nitrogen, organic matter and C/N in 0–90 cm soil depth in a greenhouse vegetable field with catch crop and straw incorporation in Fangshan, Beijing in 2014.3 after six growing seasons

Treatment	Soil depth (cm)	TN (kg ha^{-1})	OM (kg ha^{-1})	C/N
Control	0–30	5.24NS[a]	89.29NS	9.89ab
	30–60	2.61	40.59	9.05a
	60–90	2.38	34.34	8.45a
OF	0–30	4.94	80.13	9.40b
	30–60	3.00	49.72	9.62a
	60–90	1.90	25.66	7.77a
OF-WSA	0–30	4.64	84.82	10.62a
	30–60	2.65	42.93	9.35a
	60–90	1.73	31.71	10.62a
OF-SCC	0–30	4.81	80.94	9.72ab
	30–60	2.61	38.80	8.66a
	60–90	2.07	32.62	9.06a

[a]The NS means no significant difference for different treatments in the same soil profile. The different letter in the same column means significant difference for different treatments in same soil profile ($P < 0.05$)

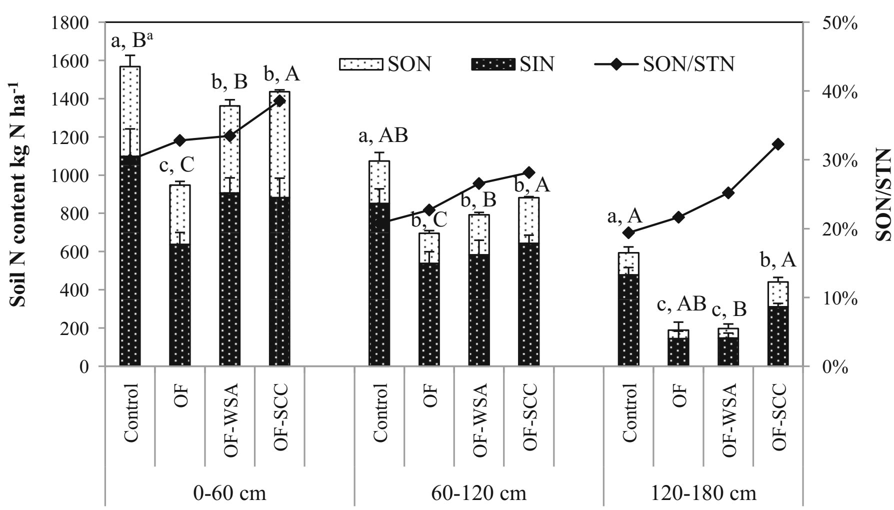

Fig. 3 Soluble inorganic N (SIN), soluble organic N (SON) and the ration of SON to soluble total N (STN) in 0–60, 60–120, 120–180 cm soil profile in a greenhouse vegetable field with catch crop and straw incorporation in Fangshan, Beijing in 2014.3 after six growing seasons. [a]Average values of SIN and SON with different lowercase (left) and uppercase (right) letters above the bars in the same growing season mean significant difference for different treatments ($P < 0.05$)

influence STN in soils compared to the control (Fig. 3), suggesting lower N losses under optimal fertigation. In contrast to STN, DPS were significantly decreased by the OF-related treatments compared to the control (Fig. 4). This suggested that optimal fertigation reduced both the accumulation and mobility of P in the rootzone, which might finally benefit plant root growth (Liang et al. 2014) and reduce potential environmental risk (Pizzeghello et al. 2011).

Effect of summer catch crop and straw application on soil N and P in the rootzone

The amount of N extracted by non-legume catch crops generally ranged from 10 to 200 kg ha^{-1} (Francis

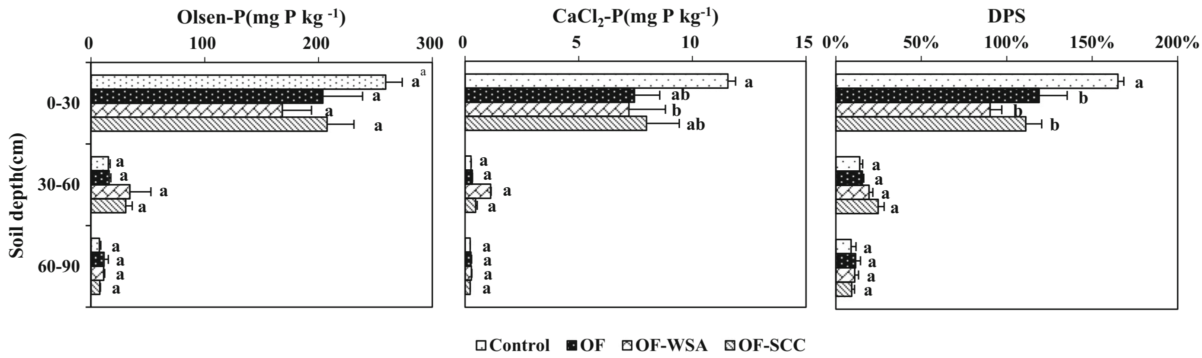

Fig. 4 Olsen-P, $CaCl_2$-P and P saturation (DPS) in 0–90 cm soil profile in a greenhouse vegetable field with catch crop and straw incorporation in Fangshan, Beijing in 2014.3 after six growing seasons. [a]The different letter means significant difference for different treatments in same soil profile ($P < 0.05$)

et al. 1995; Thorup-Kristensen 2001). In this study, summer catch crop (sweet corn) annually extracted 72–74 kg N ha^{-1} from soils. In addition to N extraction, catch crop also influenced N supply forms, because of N mineralization/immobilization induced by residue decomposition and root exudate (Fisk et al. 2015). It was estimated that more than 50% N in catch crop residue were mineralized and immobilized during the first few months after residue incorporation (Thorup-Kristensen 1994). The mineralization and immobilization of N are often thought to be closely related to soil microbial activities. Generally, plant residue supply a temporary source of available C for soil microbes (Luxhøi et al. 2007). In contrast, however, soil microbes mainly utilize soil derived N rather than plant residue-derived N (Amato and Ladd 1980). Consequently, more soil inorganic N was transformed into organic N after plant straw addition. This could partly explain the relatively high SON/SIN ratios under the OF-SCC and OF-WSA treatments in this study (Fig. 3). This phenomenon is important because the dominance of nitrate–N over SON, which was often strengthened by the N fertilizer input, could be weakened by the carbon crop residue incorporation and wheat straw application. Indeed, SON in the 0–0.6 m soil was significantly higher under the OF-SCC and OF-WSA treatments than the OF treatment (Fig. 3), thus to significantly increase SON/SIN ratio, compared to control.

In addition to soil N, soil P can also be influenced by catch crop with residue incorporation and straw application (Talgre et al. 2012). The P in plant residue is often released slowly and is not as susceptible as inorganic P fertilisers to adsorption and precipitation. Moreover, since catch crop residue and wheat straw were typically heterogeneously distributed in the soil, the immobilisation of released residue P is further hampered by the reduced contact with the soil matrix. Firstly, about 40–60% of P in crop residues is water-soluble and can be rapidly released into soils after incorporation (Talgre et al. 2012). Secondly, organic acids released from the catch crop roots and residue decomposition may help to dissolve soil mineral P and block soil P adsorption sites (Cavigelli and Thien 2003; Yong et al. 2010). Thirdly, the labile C released from roots and residues has positive effects on soil P availability in arable soils due to P mineralization driven by soil microorganisms (Jing et al. 2017). In this study, both Olsen-P and $CaCl_2$-P in soils were higher in the OF-SCC treatment than in the OF, indicating that catch crop extracted P from deep soils and residue incorporation elevated P availability in the top soil.

Effect of summer catch crop and straw application on N and P leaching

In soils, N is normally present in the form of nitrate, which can be easily absorbed by plants but also easily leach into deep soils and groundwater. Therefore, enhancing the transformation of nitrate to organic N may be an effective method to reduce N leaching during the crop growing season. This process can be achieved through plant straw/residue application because of immobilization of residual N in the rootzone. It has been demonstrated by a ^{15}N-labeling experiment, which showed that more nitrate could be transformed to organic N after sweet corn residue incorporation than non-incorporation (Guo 2007). Also, the catch crop root activity, such as rhizodeposition could be an important mechanism for organic N accumulation (Kanders et al. 2017). The root exudate C was more effective than plant residue to increase the potential for heterotrophic microbial immobilization (Fisk et al. 2015). In this study, the relatively high SON under the OF-SCC and OF-SWA treatments suggested that nitrogen leaching might be reduced by summer catch crop residue incorporation and wheat straw application (Fig. 3). Consequently, not mineral N, but dissolved organic nitrogen leaching was significantly reduced by sweet corn (Guo et al. 2018).

Compared to the nitrate, the amount of P leached downwards is often much lower (Tian et al. 2016). Yan et al. (2016) mentioned the total P leached during the experiment was 0.90–1.95 kg P ha^{-1} in greenhouses. The vast majority of P from fertilizer was remained in the soil through adsorption or precipitation. Despite this, for excessively fertilized soils P leaching still needs to be considered due to water eutrophication. In this study, Olsen-P, $CaCl_2$-P and DPS in the topsoil were increased after sweet corn planting. The increased DPS showed increased P mobility in soils with high loadings of P, which have consequently resulted in the downward transport of P with water in the soil profile (Dou et al. 2009; Pizzeghello et al. 2011). One possible explanation is that P was extracted from soils by catch crop and then mineralized into available P in the topsoil after residue incorporation (Askegaard and Eriksen 2008). The high abilities of catch crop to store P both in above-ground plant parts and roots (Talgre et al. 2012), which may cause P leaching when resist freezing damage later (Liu et al. 2014). It seems that soil P might have high leaching potential under the OF-SCC treatment. Therefore, it is very important to select appropriate catch crops without a high risk of P leaching.

Conclusion

Optimal fertigation could efficiently reduce the residual N and P through lowering the nutrient surplus. Catch crop planting could increase the soluble total N and the proportion of soluble organic N in soil residual N. The increased available nitrogen in soil showed the increased nitrogen supply capacity, and given the potential to reduce further fertilizer application. More N retained in organic form in soil with catch crop, would be an indicator for less dissolved organic nitrogen leaching, which provides quantitative insights in N retention and leaching influenced by summer catch crop in greenhouse fields. In addition, catch crop planting could enhance the availability of residual P in the rootzone, inferring a lower P input through fertigation for the succeeding crop and the target of identifying more efficient catch crops in future studies.

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