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ORIGINAL PAPER

Effect of Short-term Irrigation of Wastewater on Wheat Growth and Nitrogen and Phosphorus in Soil

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Abstract

Determine how plant age influences the effect of short-term wastewater irrigation on growth and nutrient uptake, soil available and N and P concentration. Sandy soil was left unplanted or planted with wheat and then watered with reverse osmosis (RO) water for 20 days. Wheat was planted so that plants were 7, 14 or 21 days old when half of the pots were irrigated with wastewater from days 20 to 35; the other pots received RO water until day 35. Similarly, unplanted pots received either RO or wastewater water from days 20 to 35. Irrigation with wastewater had little effect on plant dry weight, shoot N and P concentration or available N and P, and microbial biomass N and P in soil in both planted and unplanted treatments. Wastewater irrigation increased shoot N uptake compared with RO treatments only in plants that were 21 days old at the start of wastewater addition. Presence of plants reduced available nitrate up to 30-fold compared with unplanted soil. In this sandy soil, short-term wastewater irrigation had little effect on wheat growth, N and P uptake, and N and P concentration in soil. However, presence of plants reduced available N and P in soil compared with unplanted soils which would reduce potential of nutrient leaching after wastewater irrigation.

Keywords Inorganic N · Inorganic P · Growth stages · Wastewater irrigation · Wheat

1 Introduction

Wastewater derived from anthropogenic activities is an environmental concern worldwide (Bedessem et al. 2005; Gibert et al. 2008). Wastewater generated from domestic, industrial and commercial activities has increased with population and economic development (Qadir et al. 2010). Reuse of wastewater for irrigation of cropland is a common practice, especially in developing countries where technologies for wastewater treatment are limited (Castro et al. 2013) and in semi-arid and arid zones where fresh water supply is scarce (Avnimelech et al. 1993; Jalali et al. 2008). According to the FAO, approximately 10% of the world's irrigated land area receives partially treated or untreated wastewater (Cooper 2007).

Wastewater irrigation can change soil properties (Biswas et al. 2017). For example, it can reduce soil bulk density and increase soil water holding capacity, pH, EC, organic C, total N, available P and S and exchangeable cations (Na, K, Ca, Mg) compared with freshwater irrigation (Biswas et al. 2017).

However, wastewater irrigation can also result in salt and metal accumulation and nutrient leaching into ground and surface water (Avnimelech et al. 1993; Castro et al. 2013; Howarth et al. 2002; Jalali et al. 2008; Siebe and Cifuentes 1995). Wastewater application to sandy soils is particularly problematic because sandy soils have low water holding capacity, low specific surface area for adsorption and low cation exchange capacity (Hamarashid et al. 2010). Therefore, treatment of wastewater prior to irrigation, alternative irrigation and water management practices are important to avoid imbalanced nutrient supply and mitigate the harmful effects of wastewater irrigation (Castro et al. 2013; Gärdenäs et al. 2005).

Wastewater can be a source of nutrients for plant growth (Siebe and Cifuentes 1995) with the nutrient concentration depending on the source of effluent (Barreto et al. 2013; Liu and Haynes 2011). Nitrogen is high in wastewater generated by agricultural activities (Boyer et al. 2002), while P is mostly derived from industrial and residential sources (Ruzhitskaya

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and Gogina 2017). The main forms of N in wastewater are ammonium (NH_4^+-N), nitrate (NO_3^--N) and organic N (Sedlak 1991; Sotirakou et al. 1999). Orthophosphate, polyphosphate and organic compounds are the main P forms (Sotirakou et al. 1999). Therefore, irrigation with reclaimed wastewater can increase crop yield and reduce the need for chemical fertilisers which lowers production costs (Martínez et al. 2013).

Wastewater has been applied to a wide range of crops (Akhtar et al. 2012; Cereti et al. 2004). Nutrient uptake by crops can reduce the potential for nutrient leaching after wastewater irrigation (Ehdaie et al. 2010). But wastewater irrigation does not necessarily increase nutrient uptake compared with ground water irrigation (Segura et al. 2001). Nutrient uptake varies with growth stage because it depends on several factors such as nutrient demand of crops and size of root system (Ehdaie et al. 2010; Sattelmacher et al. 1993). Crop nutrient uptake can influence nutrient concentration in soil and leaching potential when wastewater is used for irrigation.

Little is known about the effect of short-term wastewater irrigation on early growth stages of crops and nutrient availability in soil. Short-term irrigation may be necessary in situations where there is a limited supply of wastewater. Farmers would then need to know how to maximise the effect of wastewater irrigation on plant nutrient uptake while minimising nutrient leaching.

The aim of this study was to determine the effect of (1) wastewater irrigation at different stages of early wheat growth on wheat dry biomass, shoot N and P concentration, N and P uptake and available N and P concentration in soil, and (2) presence of wheat plants at different growth stages on available N and P concentration in soil.

The hypotheses were (1) wastewater irrigation increases wheat growth irrespective of growth stage compared with clean water irrigation, (2) N and P uptake by wheat and available N and P in soil are higher with wastewater than clean water irrigation and (3) with wastewater irrigation, nutrient concentrations in soil are lower in planted than unplanted soil.

2 Materials and Methods

2.1 Materials

As described in Le et al. (2019), wastewater was collected from the Glenelg Sewage Treatment Plant in South Australia (longitude 138° 30′ 34.7″ E latitude 34° 56′ 44.3″ S). Effluent for the experiments was collected after primary sedimentation and passage through active sludge bioreactors (SA Water wastewater treatment plants and catchments 2013). Nitrate N, ammonium N and inorganic P concentrations in the wastewater (pH 7.0) were 15.8, 0.1 and 2.1 mg L^{-1}, respectively.

A sandy loam from Monarto in South Australia (35° 04′ S 139° 07′ E) was used. The soil was air-dried and sieved to particle size < 2 mm prior to the experiment. It has the following properties: sand 74%, silt 17%, clay 9%, total P 0.38 g kg^{-1}, pH (1:5) 7.6, total organic C 6.3 g kg^{-1}, total N 1.57 g kg^{-1}, available N 14.7 mg kg^{-1}, available P 3.4 mg kg^{-1} and maximum water holding capacity (WHC) 188 g kg^{-1}.

2.2 Experimental Design

There were eight treatments with five replicates each. Treatment factors were watering with reverse osmosis water (RO) or wastewater (W) from day 21, presence or absence of plants and age of plants. On day 0, 400 g soil (dry weight equivalent) was adjusted to 75% WHC before placing into 500-ml pots lined with plastic bags. This soil water content is optimal for microbial activity in soils of this texture according to a previous study using a sandy loam (Alamgir et al. 2012).

The pots were left either unplanted (UP) or were planted (P). For the planted treatments, 15 pre-germinated wheat seeds (*Triticum aestivum* L. variety Axe) were planted per pot on days 0, 7 or 14. After 1 week, the plants were thinned to 10 plants per pot. All pots were placed in a glasshouse with natural light where the temperature ranged from 25 to 30 °C. From day 0 to 20, soil water content of all pots was adjusted daily by weighting and adding RO water. From day 21 to day 35, half of the pots with wheat plants that were either 7, 14 or 21 days old were watered with wastewater (W).

The treatments are referred to as P7-W, P14-W and P21-W. The other half was watered with RO water, referred to as P7-RO, P14-RO and P21-RO. The unplanted pots were used to assess the effect of added wastewater on soil nutrient concentration over time in absence of plants. The unplanted pots were watered with RO water (UP-RO) from day 0 to 35 or received RO water until day 20 and then wastewater from day 21 to day 35 (UP-W). The same amount of wastewater was added daily to the respective pots (7.7 ml day^{-1}) with a total application of 115 ml.

On day 36, the plants were harvested; roots were carefully removed from the soil and washed. Then, soil in all treatments was destructively sampled to determine available N (ammonium, nitrate), available P, pH, microbial biomass N (MBN) and microbial biomass P (MBP).

2.3 Analyses

Analyses of soil texture, pH, maximum water holding capacity, total organic carbon, nitrogen, phosphorus, available N (ammonium, nitrate), available P extraction and microbial biomass N and P were carried out as described in Marschner et al. (2015) (Table 1).

Table 1 Analyses as described in Marschner et al. (2015)

Parameter	Details	Reference
Soil texture	Hydrometer method	Gee and Or (2002)
Soil pH	1:5 soil:water ratio, 1-h shaking	Rayment and Higginson (1992)
Soil maximum water holding capacity	At matric potential − 10 kPa	Wilke (2005)
Total organic C	Wet oxidation and titration	Walkley and Black (1934)
Total N	Digestion with H_2SO_4, measurement by modified Kjeldahl method	Bremner and Mulvaney (1982)
Total P	Digestion with 1:3 HNO_3 and HCl, measurement by phosphovanado-molybdate	Hanson (1950)
Available N extraction	2 M KCl at a 1:10 soil extractant ratio, 1-h shaking	
Ammonium N		Willis et al. (1996)
Nitrate N		Miranda et al. (2001)
Available P extraction	Anion exchange resin	Kouno et al. (1995)
Available P measurement		Murphy and Riley (1962)
Microbial biomass extraction	Chloroform fumigation and extraction with 0.5 M K_2SO_4	Vance et al. (1987)
Microbial biomass N	Ammonium N in extract, biomass N = (fumigated-unfumigated) × 0.57	Moore et al. (2000)
Microbial biomass P	Anion exchange resin with hexanol, biomass P = fumigated-unfumigated	Kouno et al. (1995)

Shoot and root dry weight were determined after drying at 55 °C for 48 h. Inorganic N (nitrate and ammonium) and P in the applied wastewater were determined using the same colorimetric methods as for available N and available P.

2.4 Statistical Analysis

After confirming normal distribution, the data of planted pots including shoot and root dry weight, available N and P, MBN and MBP in soil and leachate inorganic N and P were analysed by two-way analysis of variance (ANOVA) with age of plants and water source as factors. In unplanted soil, differences between water sources were tested by *t* test. For a given water source, data of unplanted soil and planted treatments were compared by *t* test. Statistical analysis was carried out in IBM SPSS Statistics 24.

3 Results

Shoot dry weight increased with the age of plants at onset of wastewater addition. Compared with P7-W (7 days of growth prior to wastewater addition), shoot dry weight was twofold higher in P14-W (14 days prior growth) and fivefold higher in P21-W (21 days prior growth) (Fig. 1(a)). Root dry weight was lowest in P7 where it was about twofold lower than in P14 and P21 (Fig. 1(b)). There was no significant difference in shoot and root dry weight between W and RO water treatments.

Shoot N and P concentration generally decreased with age of plants. Compared with P7-W, shoot N concentration was 23% lower in P14-W and 50% lower in P21-W (Fig. 1(c)). Shoot P concentration was highest in P7 treatments where it was 30–40% higher than in P14 and P21 treatments (Fig. 1(e)). Shoot N and P concentration did not differ between W and RO treatments.

Shoot N and P uptake generally was lowest in P7 treatments. Shoot N uptake in P7 was 30–40% lower than in P14 and P21 (Fig. 1(d)). Shoot N uptake differed between W and RO only in treatments P21 where it was 23% higher in P21-W than P21-RO. Shoot P uptake was about 10-fold lower than N uptake (Fig. 1(f)). It was highest in P21 where it was about 40% higher than in P7 and 20% higher than in P14. Shoot P uptake differed between W and RO treatments only in P7 where P7-W was 18% higher than in P7-RO.

Available nitrate in planted soils was low (≤ 2.1 mg kg^{-1}) and did not differ between RO and W treatments (Table 2). In unplanted soil, available nitrate was 10% higher with W than with RO water. Nitrate in unplanted soil was 15–30 times higher than in planted soil. Available ammonium was not affected by plant age at the onset of wastewater irrigation (Table 2). Available ammonium in both planted soil and unplanted soil was low (≤ 1.4 mg kg^{-1}) and did not differ between treatments with RO and with W. Available ammonium in planted soil was 20% higher than in unplanted soil in the RO treatments, but was not affected by plants in the W treatments. Available P was 24% higher in P7-W than P14-W (Table 2). It did not differ between W and RO treatments. Available P in unplanted soil was about 25% higher than in planted soil.

MBP and MBN were not affected by the age of the plants prior to wastewater irrigation. MBP did not differ between W and RO treatments (Table 2). MBN was not affected by the source of the irrigation water except in P21 where it was 20%

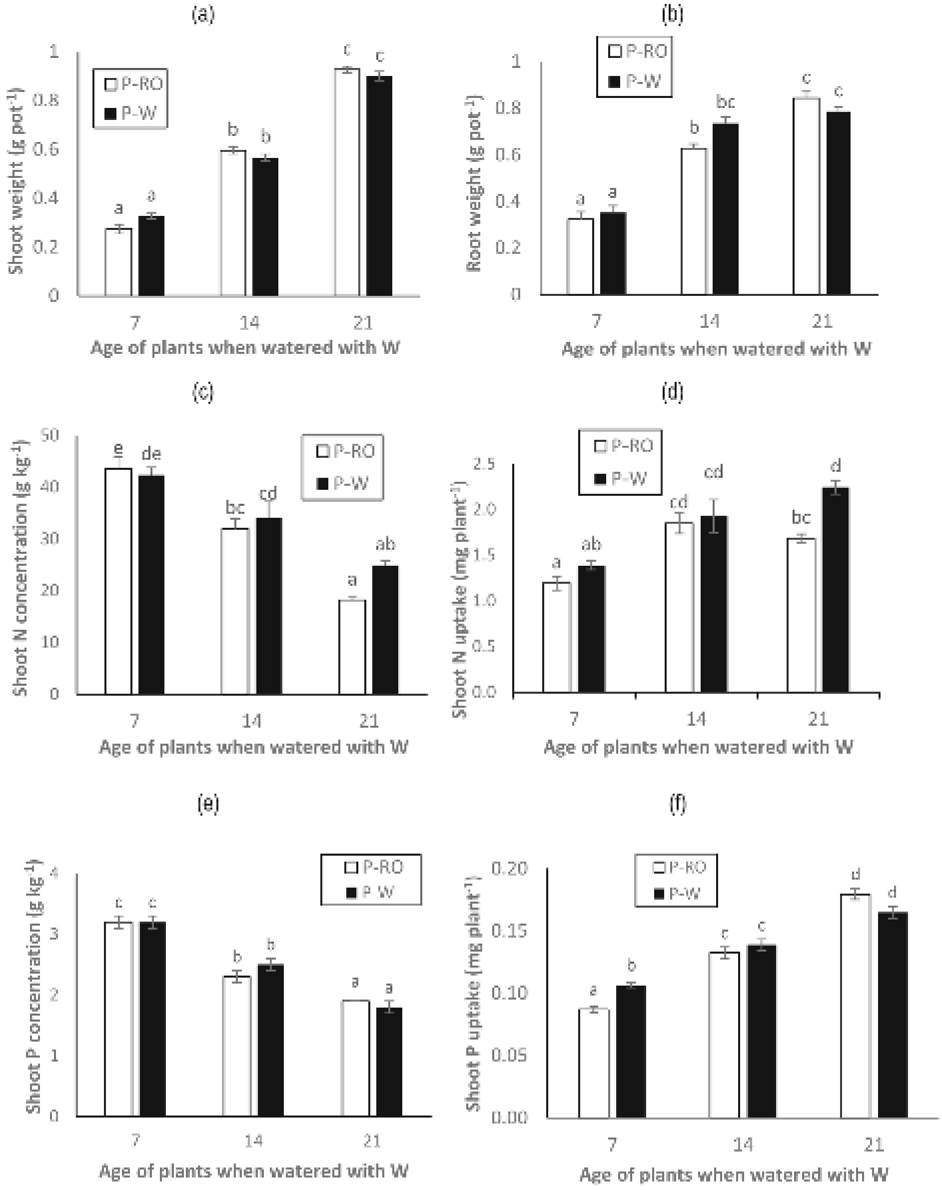

Fig. 1 Shoot dry weight (a), root dry weight (b), shoot N concentration (c), shoot N uptake (d), shoot P concentration (e) and shoot P uptake (f) of 7-, 14- and 21-day-old wheat watered with reverse osmosis water (P-RO) or with wastewater (P-W) for 14 days. Bars with different letters are significant differences between treatments (age of plants ×water source) ($n = 5$, $P < 0.05$)

higher in P21-RO than in P21-W (Table 2). MBN and MBP in planted soil were about 20% higher than in unplanted soil,

Soil pH (Table 2) ranged from 7.7 to 8.4 and was not affected by plant age. It differed little between W and RO treatments. Soil pH was about 0.3–0.6 units higher in planted than unplanted soil.

4 Discussion

Based on this study, some hypotheses can be confirmed but not for all measured parameters. In this experiment, 4.5 mg kg^{-1} inorganic N (with >95% as NO_3^--N) and 0.6 mg kg^{-1} inorganic P were added with wastewater (115 ml). This wastewater addition was not enough to increase plant growth compared with RO irrigation in this sandy soil which was relatively in high available N and P. Therefore, the first hypothesis (wastewater irrigation increases growth of wheat plants irrespective of growth stage compared with clean water irrigation) is declined.

Wastewater irrigation increased N uptake by about 20% in P21-W compared with P21-RO, but had no effect on N uptake in the plants that were younger when irrigated with wastewater. This is likely due to a greater root system of 3-week-old plants which allowed them to access more nutrients from soil that received wastewater than the younger plants. Previous studies have also shown that root biomass and plant growth

Table 2 Nitrate, ammonium, total inorganic N, available P, microbial biomass N (MBN) and P (MBP) and soil pH before leaching in soil watered with reverse osmosis water or with wastewater that was unplanted (UP-RO and UP-W) and or planted with 7-, 14- and 21-day-old wheat (P-RO and P-W) ($n = 5$, $P \leq 0.05$). In planted soil, different letters indicate significant differences between treatments (age of plants × water source). In unplanted soil, different letters indicate significant differences between reverse osmosis (RO) and wastewater (W) treatments. For a given water source, asterisk (*) indicates significantly higher value and hash (#) indicates a significantly lower value in planted compared with unplanted treatments

Age of plants when watered with W	Planted/unplanted	Nitrate (mg kg^{-1})		Ammonium (mg kg^{-1})		Available P (mg kg^{-1})		MBP (mg kg^{-1})		MBN (mg kg^{-1})		Soil pH	
		RO	W	RO	W	RO	W	RO	W	RO	W	RO	W
7	P7	2.1b#	1.5ab#	1.2a	1.2a	3.2ab#	3.7b	3.7a*	3.2a	5.6a*	5.2a*	8.3ab*	8.3ab*
14	P14	1.1a#	1.3ab#	1.3a*	1.2a	3.0ab#	2.8a#	3.8a*	3.7a*	5.7ab*	5.4a*	8.2ab*	8.2ab*
21	P21	1.1a#	1.1a#	1.4a*	1.3a	2.8a#	3.1ab#	3.8a*	3.6a*	6.6b*	5.3a*	8.2a*	8.4b*
	UP	29.4a	32.2b	1.1a	1.1a	4.2a	3.9a	2.8a	3.1a	4.5a	4.4a	7.7a	7.9b

rate influence N uptake (Ehdaie et al. 2010; Gastal and Lemaire 2002).

However, there was little difference in soil available N and P between the wastewater and RO treatments. This suggests that mineralisation of N and P of native soil organic matter was much greater than inorganic N and P added with wastewater. Hence, the second hypothesis (N and P uptake by wheat and available N and P in soil are higher with wastewater than clean water irrigation) can only be confirmed for N uptake of the 3-week-old plants.

On the other hand, soil available N and P were lower in planted than unplanted soil. This is caused by nutrient uptake of both wheat plants and soil microorganisms in planted soil. Previous studies also showed that plants reduce nutrient leaching (Ehdaie et al. 2010; Gastal and Lemaire 2002). In this study, we showed that this already occurs in young plants. Wheat plants absorb nutrients from soil for growth, reducing the nutrient concentration in soil. Further, plants also provide organic C (as roots and exudates) for microbes leading to higher microbial biomass N and P in planted than unplanted soil. The lack of difference in MBN and MBP between RO and W treatments suggests that microbes took up mainly N and P mineralised from the native SOM. Hence, the third hypothesis (with wastewater irrigation, nutrient concentrations in soil are lower in planted than unplanted soil) can be confirmed for both wastewater and RO water irrigation. This suggests that the presence of even young plants can significantly reduce the risk of nutrient leaching after wastewater irrigation.

In previous studies, we showed that addition of wheat straw to sand leached with wastewater can reduce nitrate leaching (Le and Marschner 2018; Le et al. 2019). In sand with wheat straw, leachate nitrate was at least 60-fold lower than in unamended soil. The reduction can be explained by dissimilatory nitrate reduction to ammonium and ammonium sorption to wheat straw. Hence, the results of this and our previous studies suggest that inclusion of suitable crops and/or organic amendments should be considered when wastewater is applied to sandy soils. Field trials could be undertaken to confirm these effects, including assessing nutrient retention over a longer time period than in this laboratory study.

The effect of wastewater irrigation on plant growth and available N and P may vary with soil type. It may increase plant growth in nutrient-poorer soils which have insufficient nutrient available to plants. Further, the impact of wastewater on soil nutrient concentrations and leaching potential depends on a number of factors, such as quality of the wastewater, soil characteristics and type of irrigated crops (Mojid and Wyseure 2013) as well as length of application.

5 Conclusion

This study showed that short-term wastewater irrigation had little effect on wheat plant biomass, soil MBN and MBP, and available N and P, but increased N uptake of older plants compared with RO water irrigation. It increased shoot N uptake only in plants that were 21 days when wastewater irrigation started, likely because only the older plants had sufficient roots to take up N from wastewater. Nutrient uptake by older plants and soil microorganism strongly reduced the risk of N and P leaching in this sandy soil.

Further studies are required to investigate the effect of wastewater irrigation on wheat plant growth and leaching potential in nutrient-poorer soils. In addition, studies on metal accumulation in soil and wheat plants after wastewater irrigation are needed to evaluate benefits and risks of wastewater irrigation.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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