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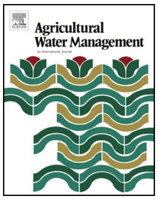

# Long-term impact of wastewater irrigation and nutrient rates II. Nutrient balance, nitrate leaching and soil properties under peri-urban cropping systems

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Since irrigation with under-treated wastewater is growing in many underdeveloped countries, its regulation should follow more efficient and less polluting approach. Therefore, the nutrient balances and soil properties were monitored in an 8-year experiment where the food grain (FGPS, paddy–wheat), fodder (FPS, sorghum-Egyptian clover) and vegetable (VPS, gourds/okra-cabbage/cauliflower) and agro-forestry (AFS, poplar–paddy–wheat) production systems were irrigated either with sewage water (SW, BOD 82 ± 11, $NO_3$–N 3.2 ± 0.4, $NH_4$–N 9.6 ± 0.5 and P 1.8 ± 0.3 mg $L^{-1}$) or good quality groundwater (GW) along with variable doses of N & P (25–100% of the recommended). The concentration and uptake of both N and P increased with SW and NP doses. SW enhanced N uptake by 29, 23, 18 and 37% in FGPS, AFS, FPS and VPS, respectively, while the corresponding values were 28, 21, 29 and 35 per cent for P uptake. The crop N removal obtained at 100% NP dose in GW were at par with 25% NP doses in AGF and VPS and 50% NP doses in FGPS and FPS with SW. The positive balances of nutrients with SW resulted in improvement in soil organic carbon and available status of nitrogen and phosphorus. Soil microbial biomass carbon (MBC) and activities of dehydrogenase, urease and phosphatase also improved substantially with SW. The most of nitrate-N was retained in the surface 0.3 m soil especially its leaching was minimal under AFS. Overall results indicated for improvement in the awareness of the growers for adjusting NP doses and non-dependent on water guzzling crops like paddy to minimise the fertiliser costs and the contamination of groundwater.

## 1. Introduction

In peri-urban areas of underdeveloped countries especially falling under the arid and semi-arid regions, wastewater irrigation provides the direct benefits for livelihood and food security of many small holder farmers. But the use of untreated or partially treated wastewater for irrigation, which has the advantages of year round availability and also the plenitude and high concentrations of essential plant nutrients, may also pose threat to farmer/consumer's health and the environment. Some of these contain heavy loads of salts to cause soil salinisation, groundwater contamination with nitrates, pathogens, heavy metals and other pollutants (Yadav et al., 2002; Rattan et al., 2005; Minhas et al., 2006; Qadir et al., 2007; Murtaza et al., 2010; Vivaldi et al., 2013). Anyhow the nutrient supplying capacity continues to be the key driver for sewage irrigation which of course is determined by the specificity of wastewater characteristics, soil type and the crops grown under the given set of agro-climatic conditions (Minhas and Samra, 2004). Wastewater induced improvements in soil fertility status and thus nutrient uptake and the crop yields have been reported widely (Chakarbharti, 1995; Friedel et al., 2000; Gog-Raj et al., 2006; Saha et al., 2010; Simmons et al., 2010; Singh et al., 2012). The wastewater affects the nutrient availability in soils in two ways: (i) by containing and adding these to soil and (ii) by contributing constitutes of sewage effluent (i.e. soluble organic and inorganic legends) that can alter soil and solution composition and processes that affect solubility, mobility, and bioavailability of nutrients (Bar-Tal et al., 2015). The added organic matter through wastewater irrigation is also presumed to influence soil microbial activity, biomass C and enzymatic activities in soil (Friedel et al., 2000).

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The main nutrients having concentrations in sewage water higher than the original fresh water are usually N, P and K. The wastewater contains N and P in organic forms that do not exist in fresh water. Therefore the plant availability of N and P applied by irrigation with wastewater and their fate in environment are different from those of N and P fertilisers (Bar-Tal, 2011; Bar-Yosef, 2011). To date, the most research on wastewater has been focused on issues related to improvement in crop yields, pathogenic contamination and heavy metal build-up ignoring yield sustainability, nutrient dynamics and changes in soils and the environmental issues (Minhas et al., 2015). Moreover, the knowledge gaps exist on the long term impacts of the wastewater irrigation on nutrient accumulations, input output balances of nutrients, carbon sequestration and nitrate movement etc. Since the wastewater irrigation will keep on growing, urban farmers are in dire need of practices that it should become more efficient and make effective use of soil fertility and fertilisers which make it less polluting. Considering these facts, the objectives of the present experiment were to evaluate the N and P balances, changes in soil properties and nitrate movement under the most common cropping systems of peri-urban areas viz. food grain, agroforestry, fodder and vegetable based systems receiving different proportions of recommended nutrients and irrigated with either domestic wastewater or good quality groundwater.

## 2. Materials and methods

### 2.1. Experimental detail

The experiment was conducted at Research Farm of Central Soil Salinity Research Institute, Karnal, India located at 75°57′E longitude and 29°43′N latitude and 243 m above mean sea level during October 2000 to April 2008. The climate at the site is subtropical semi-arid monsoonal type. The annual rainfall and open pan evaporation averaged 627 ± 57 and 1464 ± 79 mm. The soil at the site, silt-loam at the surface, is an ex-improved sodic land still having high pH (8.7–9.2) in sub-surface layers and calcareous hard pan layer of variable thickness at a depth of 0.9–1.2 m. The experiment was laid out in a double-split plot design with four replications. The 32 treatments comprised of combinations of A) four of the most prevalent cropping sequences of peri-urban areas of north-west India in main-plot, viz. (i) food grain production system (FGPS, paddy–wheat), (ii) agroforestry system (AFS, poplar–paddy–wheat), (iii) fodder production system (FPS, sorghum-Egyptian clover) and (iv) vegetable production system (VPS, okra/gourds during summer and cabbage/cauliflower during winter); B) two qualities of irrigation water in sub-plots, viz. (i) sewage effluent (SW) and (ii) good quality ground water (GW) and C) four fertiliser levels in sub-subplots viz. (i) 25, 50, 75 and 100% dose of recommended fertiliser nitrogen (N) and phosphorus (P). The plot size was 7.5 m × 4.0 m. To avoid the side effects on the adjoining annual crops, a separate block was assigned to agroforestry system. Only the recommended doses of NP were applied to the first year crops i.e. during the year 2000–01 and thereafter the fertiliser (N:P) doses were; 50:50, 100:50, 50:100 and 100:100 per cent of recommended until winter season of 2003–04. Due to low use efficiency of added nutrients particularly P, the effects of various fertiliser treatments were not conspicuous during 2001–02 and 2002–03. Therefore, the NP 50:100, 100:50 treatments were changed to 25:25 and 75:75. The recommended doses of fertiliser N, P and K were 120, 26 and 33 kg ha$^{-1}$ for paddy, wheat and sorghum whereas these were 20, 31 and 33 kg ha$^{-1}$ for Egyptian clover. Similarly the recommended doses of N, P and K for winter vegetables (cabbage/cauliflower) were 150, 35 and 50 kg ha$^{-1}$ whereas for summer vegetables, these were 120, 26, and 33 kg ha$^{-1}$ in okra, 80, 26 and 42 kg ha$^{-1}$ in bottle gourd, sponge gourd and ridge gourd. The details of other agronomic practices are described in Minhas et al. (2015).

### 2.2. Analysis of crop, water and soil samples

After the crop harvest, air dried grain and straw samples of wheat and rice were washed with distilled water and dried in the oven at 60 °C till the constant weights achieved. Similarly, fresh sub samples from the edible parts of the crops i.e. bolls of cabbage, curd of cauliflower, fruits of okra and gourds, plants of Egyptian clover and sorghum were air dried, washed with distilled water and finally dried in the oven. Plot wise vine biomass in gourds, stalks of okra, leaves of cabbage and cauliflower were collected and recorded their fresh and dry biomass. Oven dried plant samples were finely ground, digested in di-acid (nitric and $HClO_4$) and analysed for phosphorus content using vanado-molybdophosphoric yellow colour method. Plant samples were also digested in $H_2SO_4$ and analysed for nitrogen concentration. Carbon contents in different components of poplar were determined by dry combustion using Elementar make CHNS analyser.

Soil samples were collected from each plot after the crop harvest, air dried, passed through 2 mm sieve and analysed for various parameters. The soil pHs and electrical conductivity (ECe) were determined as per methods described by Richards (1954). Organic carbon (OC) was determined by wet digestion method (Walkley and Black, 1934). Available nitrogen and phosphorus were estimated using the method given by Subbiah and Asija (1956) and Olsen et al. (1954), respectively. For $NO_3$—N, soil samples were drawn down to 2.40 m at the end of the experiment and analysed using MgO and Devarda's alloy. Dehydrogenase activity (DHA) in surface soil was determined as per Casida et al. (1964) procedure using 2,3,5-triphenyltetrazolium chloride (TTC) and expressing the results in micrograms triphenyl formazan (TPF) per gram soil. The size of microbial biomass carbon (MBC) was estimated by fumigation-incubation technique (Jenkinson and Powlson, 1976); a conversion factor of 0.45 was used to calculate MBC. Both DHA and MBC were expressed on an oven dry basis. The enzyme activities of urease and alkaline phophatase were estimated by the methods given by Tabatabai and Bremner (1972) and Tabatabai and Bremner (1969), respectively.

All the crops were grown under irrigated conditions as per quality of water. The composition of both SW and GW was analysed at monthly interval. Measurements for biochemical oxygen demand ($BOD_5$) and chemical oxygen demand (COD) were carried by using standard methods as proposed by APHA (1992). Nitrogen content in water samples was determined through nitrogen analyser. The P content was measured by ascorbic acid method using colorimeter, whereas K was measured using flame photometer. Besides this, total trace metal (Fe, Mn, Zn, Cu, Cd, Cr, Ni, and Pb) concentrations in di-acid ($HNO_3$ and $HClO_4$) digested water samples were estimated with atomic absorption spectrophotometer. The SW had BOD 82 ± 11 mg L$^{-1}$ and COD 136 ± 14 mg L$^{-1}$ while these were below detectable levels in GW. *Fecal coliforms* in sewage were 1.5 ± 0.3 × $10^6$ cfu mL$^{-1}$. The EC of SW was 1.3 ± 0.3 dS m$^{-1}$ while $NO_3$—N, $NH_4$—N, P and K contents averaged 3.2 ± 0.4, 9.6 ± 0.5, 1.8 ± 0.3 and 6.4 ± 0.4 mg L$^{-1}$, respectively. EC of GW was 0.6 ± 0.2 dS m$^{-1}$ and its P and K contents were 0.03 and 3.5 ± 0.3 mg L$^{-1}$. Fe, Zn and Cu contents in sewage averaged 0.9, 0.2 and 0.1 mg L$^{-1}$, respectively whereas contents of Cd, Ni, Pb and Cr were in traces. Total N and P added through fertilisers and irrigation water in different cropping systems is included in Table 1. During eight cycles of winter crops, 273, 480 and 187 ha-cm of irrigation water was applied in wheat, Egyptian clover and winter vegetables, respectively, which simultaneously added 350,

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**Table 1**
Total N and P added (kg $ha^{-1}$) through fertilizers and sewage water irrigation.

| NP dose (%) | FGPS | | FPS | | AFS | | VPS | |
|---|---|---|---|---|---|---|---|---|
| | Wheat | Paddy | Clover | Sorghum | Wheat | Paddy | Winter | Summer |
| Nitrogen | | | | | | | | |
| 25 | 390 | 360 | 65 | 30 | 320 | 296 | 488 | 300 |
| 50 | 540 | 480 | 90 | 480 | 444 | 394 | 675 | 480 |
| 75 | 810 | 720 | 110 | 720 | 666 | 592 | 1012 | 560 |
| 100 | 960 | 840 | 150 | 840 | 789 | 690 | 1200 | 640 |
| SW | 350 | 1131 | 615 | 215 | 288 | 929 | 242 | 461 |
| Phosphorus | | | | | | | | |
| 25 | 111 | 104 | 132 | 104 | 91 | 85 | 149 | 104 |
| 50 | 117 | 104 | 140 | 104 | 96 | 85 | 158 | 104 |
| 75 | 150 | 130 | 178 | 130 | 123 | 107 | 201 | 130 |
| 100 | 208 | 182 | 248 | 182 | 171 | 150 | 280 | 182 |
| SW | 50 | 161 | 88 | 31 | 41 | 132 | 34 | 63 |

615 and 242 kg of N and 50, 88 and 34 kg of P in case of SW. Similarly in 7 crop cycles of summer crops, 882, 168 and 255 ha-cm of irrigation water was applied to paddy, sorghum and summer vegetables, respectively, which also added 1131, 215 and 461 kg of N and 161, 31 and 63 kg of P in case of SW. In agroforestry system, 18% of the area was occupied by ridges created for poplar trees and thus irrigation applied equalled 224 ha-cm in wheat and 723 ha-cm in paddy that also added 287 kg N and 41 kg P in wheat and 929 kg N and 131 kg P with SW. N and P uptake (kg per hectare) by different crops were computed by summing the products of dry weight of plant components with their respective concentrations. Similarly, for calculating carbon removal by poplar trees, oven dry masses of timber, fuel wood and twigs/leaves and leaf fall were recorded and multiplied by their respective carbon contents determined by CHNS analyser. Net balances of nitrogen and phosphorus in a crop during the experiment were calculated by subtracting amount of crop nutrient taken by the both the crops in a given cropping system from the amount of that nutrient added in the soil through fertiliser and irrigation water. Amount of nutrients contributed through irrigation water was obtained as a product of total amount of irrigation water applied during the study period with average nutrient concentration in sewage and groundwater. Significance of differences in crop nutrient contents, their uptake and soil properties in response to the effects of quality of irrigation and fertiliser doses in different cropping systems were assessed by computing the analysis of variance between treatment means at 5% level of significance by the method given by Gomez and Gomez (1984). Depth wise nitrate-N contents in soil were analysed by Duncan multiple range test.

## 3. Results

### 3.1. Nutrient budgeting

The average contents of N in economic parts (grain in paddy and wheat, above ground biomass in clover and sorghum and fruit in vegetables) of crops under different cropping systems are given in Table 2. N contents was improved in crops grown with SW e.g. it averaged 1.82 and 1.74% in wheat grains under FGPS and AFS when irrigated with SW compared with 1.67 and 1.60% with GW. Similarly in other crops, the N contents increased by 0.08–0.26 per cent over their respective contents with GW. NP fertilisers also increased N contents of crops except in Egyptian clover and these were more prominent in crops receiving GW and at lower doses. With both higher N contents and also the improved yields, the total N uptake improved with SW and the doses of NP while their interactive effects were non-significant except in FGPS. Since the harvested biomass was more and clover being a leguminous crop, the total N removal was highest (3699 kg $ha^{-1}$) under FPS while it ranged between 1397 and 1642 kg $ha^{-1}$ under the other cropping systems. When averaged for the two water qualities, the uptake improved by about 25% with SW irrigation. Similarly the N removal improved by 13.0, 20.9 and 31.0 per cent with the application of NP doses of 50, 75 and 100% over the 25%, respectively, when irrigated with GW and the counter figures with SW were 8.0, 13.4 and 207 indicating lower response to fertilisers in the latter.

On the whole there was a net depletion of 332–378 kg N $ha^{-1}$ when FGPS was irrigated with GW (Fig. 1) and supplied with 25–50% fertilisers and thereafter the net balance was almost nil. However, there was a net addition of 610 to 1229 kg N $ha^{-1}$ with SW irrigation. Similar trends in N balances were observed in AGFS. Considering the N removal through bole, branches, twigs and roots of poplar i.e. 264 kg N $ha^{-1}$, enrichment ranged between 513 to 1093 kg N $ha^{-1}$ with SW. The clover being a leguminous crop and its total biomass removals being markedly higher, the N accumulations in its above ground parts averaged 2440 and 2877 kg $ha^{-1}$ and therefore there was a net negative balance of N in FPS that ranged between 2319 and 3057 kg $ha^{-1}$. However there were net additions of N under the VPS except for 25–50% dose under GW irrigation. The net addition with SW irrigation averaged 432 kg $ha^{-1}$.

Similar to nitrogen, the P contents improved in crops grown with SW especially those where economic produce was the non-grain component e.g. it averaged 0.62, 0.60 and 0.56% in clover, cabbage/cauliflower and gourds irrigated with SW compared with 0.53, 0.52 and 0.49 with GW (Table 3). NP fertilisers also increased P contents of crops especially in wheat grains. However, there were little difference in P contents in case of paddy, Egyptian clover and gourds. The total P uptake also improved with SW and the doses of NP while their interactive effects were non-significant except in wheat under FGPS. The total P removal was highest (610 kg $ha^{-1}$) under FPS while it ranged between 246 and 282 kg $ha^{-1}$ under the other cropping systems. When averaged for the two water qualities, the uptake improved by about 30% with SW irrigation. The P removal improved by 14.4, 22.6 and 34.8 per cent with the application of NP doses of 50, 75 and 100% over the 25%, respectively, when irrigated with GW and the counter figures with SW were 4.9, 8.2 and 13.9 indicating lower response to fertilisers in the latter. On an average, net depletion of P was monitored only in case of FPS where it was 272 and 322 kg $ha^{-1}$ when irrigated with GW and SW, respectively (Fig. 2). In other cropping systems, the net additions when averaged for doses equalled 28, 32 and 81 kg $ha^{-1}$ under FGPS, AFS and VPS irrigated with GW while the counter figures were 170, 166 and 92 kg $ha^{-1}$, respectively.

### 3.2. Changes in soil properties

One of the major constraints for sewage irrigation includes its negative impacts on soil quality in terms of accumulation

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**Table 2**
N contents and its removal by crops under different cropping system.

| NP dose (%) | FGPS (grain) | | | | AFS (grain) | | | | FPS (plants) | | | | VPS (fruit) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Wheat | | Rice | | Wheat | | Rice | | Clover | | Sorghum | | Cab./Cauli | | Gourds | |
| | GW | SW | GW | SW | GW | SW | GW | SW | GW | SW | GW | SW | GW | SW | GW | SW |
| N content (%) | | | | | | | | | | | | | | | | |
| 25 | 1.60 | 1.78 | 1.31 | 1.41 | 1.56 | 1.72 | 1.30 | 1.41 | 3.01 | 3.19 | 1.22 | 1.30 | 2.67 | 2.98 | 1.53 | 1.74 |
| 50 | 1.67 | 1.79 | 1.32 | 1.40 | 1.59 | 1.74 | 1.33 | 1.42 | 3.03 | 3.14 | 1.22 | 1.34 | 2.77 | 3.02 | 1.61 | 1.81 |
| 75 | 1.70 | 1.85 | 1.38 | 1.44 | 1.62 | 1.74 | 1.38 | 1.42 | 3.03 | 3.18 | 1.26 | 1.34 | 2.83 | 3.10 | 1.67 | 1.80 |
| 100 | 1.72 | 1.86 | 1.40 | 1.46 | 1.64 | 1.76 | 1.39 | 1.44 | 3.00 | 3.23 | 1.26 | 1.35 | 2.88 | 3.10 | 1.71 | 1.83 |
| Mean | 1.67 | 1.82 | 1.35 | 1.43 | 1.60 | 1.74 | 1.35 | 1.42 | 3.02 | 3.18 | 1.24 | 1.33 | 2.79 | 3.05 | 1.63 | 1.79 |
| LSD ($p = 0.05$) | | | | | | | | | | | | | | | | |
| WQ | 0.05 | | 0.03 | | 0.03 | | 0.02 | | 0.03 | | 0.02 | | 0.06 | | 0.03 | |
| Doses | 0.05 | | 0.02 | | 0.04 | | 0.01 | | NS | | 0.02 | | 0.07 | | 0.03 | |
| WQ × dose | NS | | 0.02 | | NS | | 0.02 | | NS | | NS | | NS | | 0.05 | |
| N removed (kg ha$^{-1}$) | | | | | | | | | | | | | | | | |
| 25 | 599 | 892 | 529 | 729 | 513 | 689 | 278 | 367 | 2319 | 2770 | 804 | 998 | 636 | 933 | 308 | 470 |
| 50 | 756 | 1013 | 596 | 770 | 605 | 769 | 318 | 406 | 2437 | 2842 | 915 | 1091 | 782 | 1074 | 358 | 514 |
| 75 | 873 | 1106 | 674 | 834 | 670 | 816 | 354 | 438 | 2466 | 2838 | 988 | 1186 | 822 | 1122 | 391 | 557 |
| 100 | 981 | 1173 | 737 | 879 | 706 | 870 | 378 | 468 | 2537 | 3057 | 1082 | 1260 | 972 | 1184 | 445 | 586 |
| Mean | 802 | 1046 | 634 | 803 | 623 | 786 | 332 | 420 | 2440 | 2877 | 947 | 1134 | 803 | 1078 | 376 | 532 |
| LSD ($p = 0.05$) | | | | | | | | | | | | | | | | |
| WQ | 33 | | 27 | | 39 | | 18 | | 96 | | 62 | | 32 | | 23 | |
| Doses | 38 | | 26 | | 26 | | 14 | | NS | | 43 | | 46 | | 20 | |
| WQ × dose | 54 | | NS | | NS | | NS | | NS | | NS | | NS | | NS | |

of heavy metal ions and the contamination of groundwater. However, the sewage utilised for this experiment was from domestic and its heavy metal contents were below the permissible limits. The changes in soil properties (surface 0.3 m soil) monitored after 8 years are shown in Fig. 3. The benefits of SW were obvious in terms of increase in organic carbon and the available status of N, P and K. Mean values of organic carbon in groundwater irrigated soil increased from its initial content of 0.42 to 0.45, 0.50 and 0.54% under VPS, FPS and AFS, respectively. Under SW irrigation, organic carbon further improved to 0.62% under AFS while it ranged between 0.57 and 0.59% under the other cropping systems. At 25% of recommended NP doses, organic carbon contents were the lowest both under SW and GW irrigated soils. The soil pHs varied between 7.8 and 8.2 and values being higher in SW than GW irrigated soils. The average ECe was also 1.2 to 1.5 times higher under SW compared with GW irrigated soils. Available soil N, P and K improved with SW. The average available N, P and K ranged between 183–187, 31–36 and 239–254 kg ha$^{-1}$ in SW irrigated soils whereas the corresponding values were 133–148, 17–21 and 198–212 kg ha$^{-1}$ with GW. The NP also got depleted at reduced doses while the values improved at recommended doses. However, the contents of available K were unaltered. Comparing different cropping systems, available N, P and K values were the highest in AFS both with SW and GW.

Soil microbial biomass carbon (MBC) and activities of dehydrogenase, urease and phosphatase in surface 0.3 m soil improved with SW (Table 4). Dehydrogenase activities ranged from 104 to 127 and 120 to 154 μg TPF g$^{-1}$ in GW and SW irrigated soils, respectively. Urease and phosphatase activities also increased by 4 to 15% and 6 to 17% with SW. Amongst different cropping systems, enzymatic activities and soil microbial biomass were higher in soils under AFS and FPS compared with FGPS and VPS both with GW and SW irrigation. Average soil microbial biomass was about 1.3 times more in SW irrigated soil compared with GW. In case of SW irrigation, values were the lowest in VPS (322 mg kg$^{-1}$) and highest in AGF (389 mg kg$^{-1}$). Similar trend was recorded with GW.

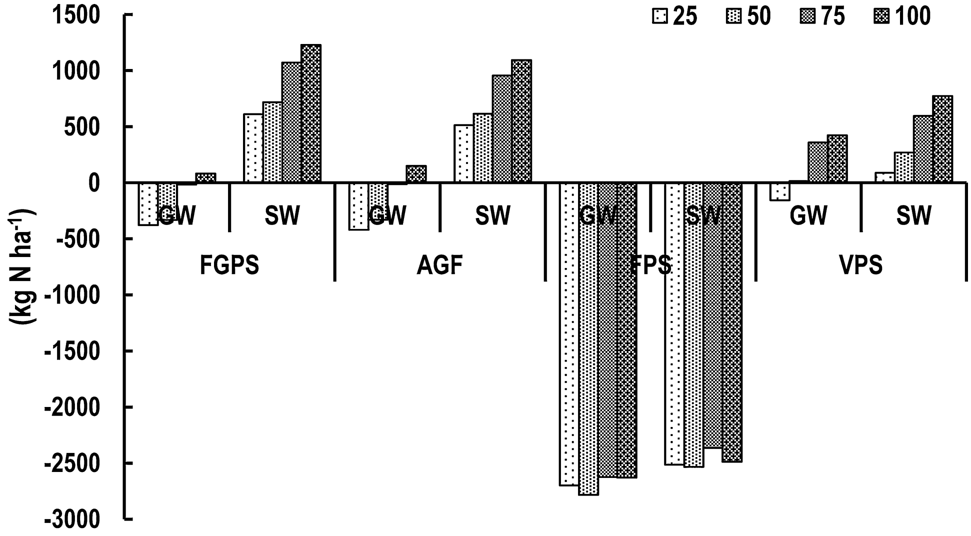

**Fig. 1.** Nitrogen balance in different cropping systems.

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**Table 3**
P contents and its removal by crops under different cropping system.

| NP dose (%) | FGPS (Grain) | | | | AFS (Grain) | | | | FPS (Plants) | | | | VPS (Fruits) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Wheat | | Rice | | Wheat | | Rice | | Clover | | Sorghum | | Cab./Cauli | | Gourds | |
| | GW | SW | GW | SW | GW | SW | GW | SW | GW | SW | GW | SW | GW | SW | GW | SW |
| P content (%) | | | | | | | | | | | | | | | | |
| 25 | 0.37 | 0.40 | 0.16 | 0.18 | 0.38 | 0.42 | 0.16 | 0.17 | 0.52 | 0.62 | 0.18 | 0.22 | 0.47 | 0.57 | 0.48 | 0.57 |
| 50 | 0.40 | 0.41 | 0.17 | 0.18 | 0.40 | 0.44 | 0.16 | 0.17 | 0.53 | 0.63 | 0.17 | 0.22 | 0.52 | 0.61 | 0.49 | 0.56 |
| 75 | 0.40 | 0.42 | 0.17 | 0.18 | 0.41 | 0.43 | 0.16 | 0.17 | 0.54 | 0.63 | 0.20 | 0.21 | 0.53 | 0.61 | 0.49 | 0.57 |
| 100 | 0.41 | 0.42 | 0.17 | 0.18 | 0.42 | 0.44 | 0.17 | 0.17 | 0.53 | 0.63 | 0.21 | 0.20 | 0.55 | 0.62 | 0.51 | 0.55 |
| Mean | 0.39 | 0.41 | 0.17 | 0.18 | 0.40 | 0.44 | 0.16 | 0.17 | 0.53 | 0.62 | 0.19 | 0.21 | 0.52 | 0.60 | 0.49 | 0.56 |
| LSD($p = 0.05$) | | | | | | | | | | | | | | | | |
| WQ | 0.01 | | 0.01 | | 0.01 | | NS | | 0.01 | | 0.01 | | 0.05 | | 0.02 | |
| Doses | 0.02 | | NS | | 0.01 | | NS | | NS | | 0.02 | | 0.05 | | NS | |
| WQ × dose | NS | | NS | | NS | | NS | | NS | | NS | | NS | | NS | |
| P removal (kg ha$^{-1}$) | | | | | | | | | | | | | | | | |
| 25 | 121 | 193 | 71 | 106 | 95 | 138 | 41 | 54 | 406 | 545 | 121 | 167 | 100 | 157 | 89 | 138 |
| 50 | 154 | 198 | 83 | 108 | 116 | 144 | 46 | 57 | 426 | 564 | 129 | 176 | 133 | 178 | 110 | 146 |
| 75 | 175 | 210 | 90 | 117 | 127 | 149 | 48 | 60 | 439 | 558 | 154 | 183 | 138 | 178 | 116 | 166 |
| 100 | 202 | 218 | 99 | 121 | 135 | 152 | 53 | 63 | 452 | 594 | 177 | 193 | 166 | 192 | 132 | 173 |
| Mean | 163 | 205 | 86 | 113 | 118 | 146 | 47 | 59 | 431 | 565 | 145 | 180 | 134 | 176 | 112 | 156 |
| LSD ($p = 0.05$) | | | | | | | | | | | | | | | | |
| WQ | 11 | | 8 | | 6 | | 3 | | 10 | | 14 | | 23 | | 10 | |
| Doses | 10 | | 5 | | 6 | | NS | | 20 | | 11 | | 20 | | 8 | |
| WQ × dose | 14 | | NS | | NS | | NS | | NS | | NS | | NS | | NS | |

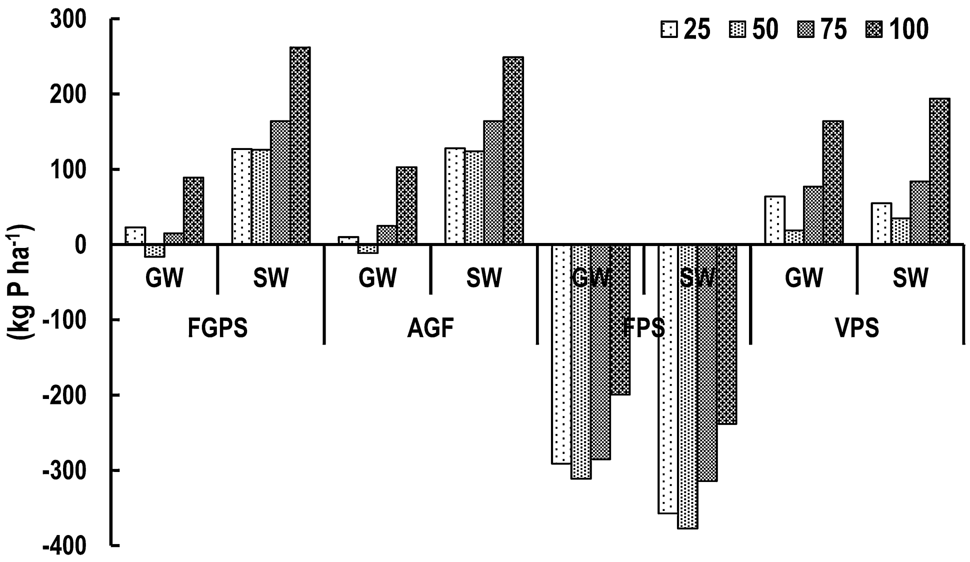

**Fig. 2.** P balance in different cropping systems.

**Table 4**
Changes in microbiological properties of soil.

| NP dose (%) | DHA (μg TPF g$^{-1}$ soil 24 h$^{-1}$) | | | Urease (μg NH$_4$—N g$^{-1}$ soil) | | | Phosphatase (μg *p*-nitrophenol g$^{-1}$ soil) | | | MBC (mg kg$^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SW | GW | Mean | SW | GW | Mean | SW | GW | Mean | SW | GW | Mean |
| FGPS | 130.3 | 107.9 | 119.1 | 54.9 | 51.7 | 53.3 | 165.8 | 151.8 | 158.8 | 369.8 | 281.3 | 325.5 |
| FPS | 155.9 | 111.0 | 133.5 | 70.1 | 63.9 | 67.0 | 206.7 | 180.5 | 193.6 | 362.0 | 265.3 | 313.6 |
| VPS | 120.5 | 104.2 | 112.4 | 59.3 | 59.1 | 59.2 | 179.3 | 167.4 | 173.4 | 309.0 | 241.8 | 275.4 |
| AFS | 155.6 | 127.3 | 141.5 | 74.5 | 62.7 | 68.6 | 205.1 | 177.5 | 191.3 | 383.0 | 287.3 | 335.1 |
| Mean | 140.6 | 112.6 | 126.6 | 64.7 | 59.3 | 62.0 | 189.2 | 169.3 | 179.3 | 355.9 | 268.9 | 312.4 |
| LSD ($p = 0.05$) | | | | | | | | | | | | |
| | | 7.4 | | | 8.9 | | | 3.8 | | | 27.3 | |
| | | 8.0 | | | 8.1 | | | 18.7 | | | 35.8 | |
| | | 11.2 | | | NS | | | NS | | | NS | |

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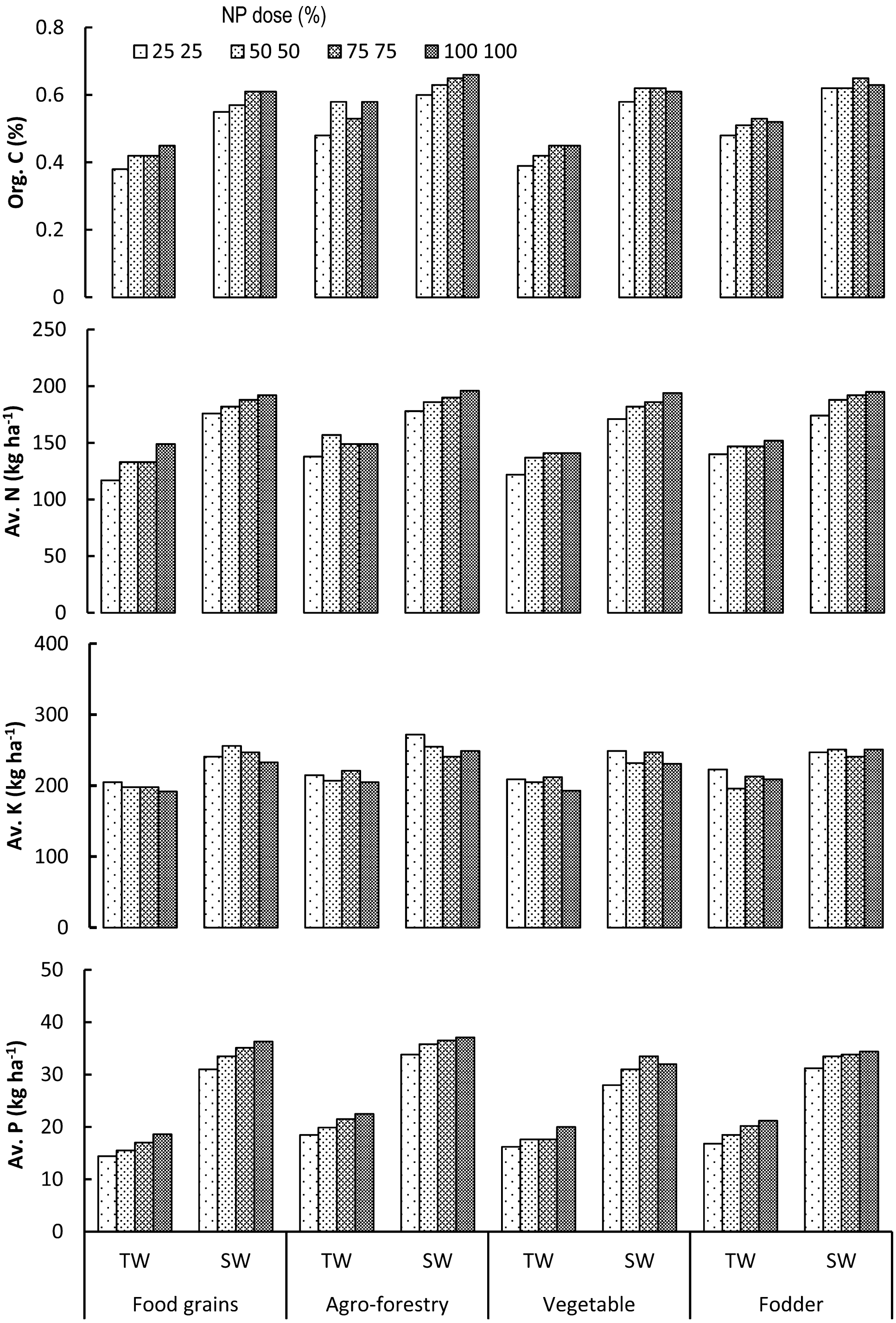

**Fig. 3.** Organic carbon and available macronutrients contents in surface 0.30 m soil after 8 years of different cropping systems and nutrient rates.

The depth distribution of $NO_3$—N showed higher contents in SW irrigated soils (Fig. 4) e.g. it ranged between 58.8 to 67.3 and 42.6 to 56.0 mg kg$^{-1}$ in surface 0.15 m of SW and GW irrigated soils, respectively. In general, the contents decreased with soil depth and were about 22–39 and 20–27 mg kg$^{-1}$ in soil below 1.2 m with SW and GW irrigation. Sudden dips indicating the higher rooting vis-à-vis N uptake varied with the cropping systems. These were 0.3–0.6 m soil layer under FGPS and FPS, 0.6–0.9 m in VPS while 0.3–6 and 0.6–0.9 m soil layers under AFS system. Amongst different cropping systems, highest $NO_3$-N was monitored in surface 0.3 m soils under AFS while lowest contents in soil below 1.5 m indicating higher tapping of $NO_3$—N by the same system.

## 4. Discussion

The wastewater contains high concentrations of nutrients those get recycled when used for irrigation. Thus the farmers usually get benefitted in terms of not only saving fertilisers but improving soil fertility. This has an additional benefit to the society by reducing greenhouse gases produced during manufacture and supplies of fertilisers especially the nitrogenous (Fine and Hadas, 2012). However, the overdoses of fertilisers along with wastewater irrigation and their low efficiency can lead to environmental issues through simultaneous accumulations of pollutants and later leaching to groundwater. Thus the basic concept underlying the

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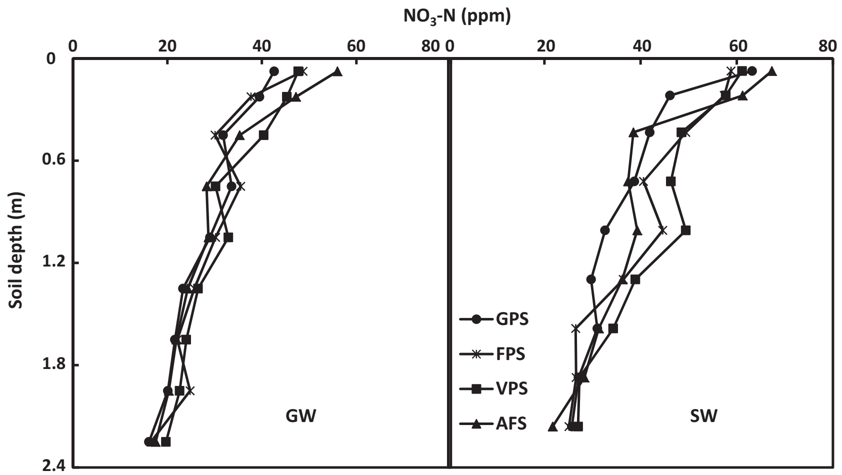

**Fig. 4.** Depth distribution of $NO_3$—N in soils under different crops irrigated with GW and SW.

wastewater management should remain the maintenance and possible improvement in soil fertility and also reduction of fertiliser input while sustaining crop productivity on long term basis and minimising environment impacts. Since N and P are the main nutrients which the sewage has higher concentrations than fresh waters and also in organic forms, their fate in soils is different than those in inorganic fertilisers (Bar-Tal, 2011). In the present experiment, as high as 160 kg N and 23 kg P $ha^{-1}$ were added to each crop of paddy with SW irrigation, the most water proliferate amongst the crop grown. The N added ranged from 30 to 77 and P from 5 to 11 kg $ha^{-1}$ in other crops that was equivalent to 25 to 50% N and 20 to 40% P requirements. These additions boosted the growth of plants and resulted in an overall improvement in the crop productivity by 22, 18, 14 and 28 per cent in FGPS, FPS, AFS and VPS, respectively (Minhas et al., 2015). Nutrient crop removal, which is the product of nutrient concentration and crop biomass, was considerably improved by SW (Tables 1 and 2). Higher content, uptake of N and P and better crop growth with increasing fertiliser doses and sewage use have also been reported earlier (Chakarbharti, 1995; Juwarkar et al., 1991; Gupta and Mitra, 2002; Simmons et al., 2010) while other (Chakarbharti and Chakarbharti, 1988) reported soil sickness induced reductions in wheat growth as a result of excessive organic and nitrogen loading causing anaerobiosis and imbalance in C:N and C:P ratios. Several others (Ensink et al., 2002; Gog-Raj et al., 2006; Simmons et al., 2010) have reported that response and N uptake of various crops to N in wastewater was not different from the applied fertiliser N but synchronisation of N supply through wastewater has to be maximised with growth rate and N consumption of crops to minimise the movement of residual N and groundwater contamination. Especially the irrigation of summer crops when mineralisation rates of organically bound N are high will increase the potential for pollution of groundwater with nitrogen. However, the simultaneous build-up of organic carbon in soils seems to have helped to retain the most of the added NP with SW (Fig. 3) though the negative balances of NP especially at lower fertiliser doses and with GW irrigation resulted in decline in their available contents in soils. Otherwise in general there was increase soil organic carbon and available N and P in soils. Long term application of recommended NP fertilisers in the region has earlier been reported to result in improvements in the soil organic carbon and available NPK status due to rhizo-depositions, additions of root biomass and the above ground stubbles etc (Benbi and Brar, 2009; Brar et al., 2013). This specifically holds for SW irrigation that also substantially adds the organic carbon and the nutrients (Al-Omron et al., 2012; Datta et al., 2000; Mohammad and Majahreh, 2003; Rattan et al., 2005; Singh et al., 2012; Bar-Tal et al., 2015). Increased soil microbial biomass C and activities were also due to the larger application of organic matter with SW (Friedel et al., 2000; Ramirez-Fuentes et al., 2002). Increase in soil MBC with increase in fertilisers doses also was reported by Haynes (2005). The $NO_3$–N accumulations and distribution in soil (Fig. 4) were controlled mainly by the crop removal and N additions through SW irrigation while the rooting patterns further affected the depth distribution of $NO_3$—N e.g. the $NO_3$—N contents in surface 0.3 m ranged from 46.1 to 67.3 mg $kg^{-1}$ with SW and 37.7 to 56.0 mg $kg^{-1}$ with GW irrigation. Deep and extensive root system of trees under AFS enabled to absorb substantial quantities below the rooting zone of crops and thus checked the downward movement of N. Similar observations have earlier been made by Allen et al. (2004), Simmons et al. (2010).

## 5. Conclusion

The wastewater irrigation offers opportunities for effective utilisation of otherwise un-exploited nutrients along with water. Combining wastewater with judicious use of inorganic fertilisers can be a strategic intervention for sustainable crop productivity and reducing the potential for environmental pollution. The monitoring of long term changes indicated the improvement in soil quality in terms of build-up of carbon, nitrogen and phosphorus in soils with sewage irrigation even with reduced doses of NP fertilisers whereas there were net negative balances with groundwater irrigation. Understanding the processes of nitrate leaching and introduction of deeper rooted trees or other crops can minimise the ground water contamination. Nevertheless, the awareness of the growers for adjusting NP doses and no-dependent on water guzzling crops like paddy seems essential.

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