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Does Turbulent-flow Conditioning of Irrigation Water Influence Soil Chemical Processes: II. Long-term Soil and Crop Study

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ABSTRACT

Recent laboratory evidence suggests that the intrinsic behavior of molecular water in soil is altered by turbulent-flow conditioning (CTap) of mineralized irrigation water (Tap). This 9-yr (2009 to 2017), irrigated, outdoor, cropped pot study evaluated the effect of Tap and CTap irrigation water on soil leachate chemistry, nutrient availability, and aboveground crop biomass yield and nutrient uptake. CTap increased cumulative mass losses of: nitrate nitrogen 2.5-fold; manganese 2-fold; potassium (K) 1.6-fold; magnesium (Mg), dissolved organic carbon, and ammonium nitrogen (NH_4-N) an average 1.2-fold; and increased the mean electrical conductivity of leachate 1.2-fold. In both the current and a previous laboratory study (see Part 1), K, NH_4-N, and Mg were leachate components most consistently selected by multivariate analysis as best discriminating between water treatments. The evidence also suggests that CTap increased mean available soil zinc (Zn) 2.4-fold, copper, K, and soil phosphorus an average 1.4-fold, sodium and iron (Fe) 1.2-fold, and decreased soil total carbon, TC (4%), total inorganic carbon (8%) and Mg (9%) relative to the Tap. In addition, CTap increased average crop biomass element concentrations: Zn, Fe, and aluminum an average 1.3-fold; total nitrogen, calcium, K, and sulfur 1.1-fold; and decreased TC (2%) relative to Tap. If the capacity of this simple device to increase soil cation leaching can be confirmed in broader applications, it could potentially provide an economical means of increasing the availability of nutrients in soils irrigated with conditioned water and managing or remediating degraded, salt-affected soils.

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Introduction

The chemical composition of irrigation water and the amount and rate of irrigation applied can influence soil chemistry and crop productivity in agricultural fields (Al-Ghobari, 2011; Amundson and Smith 1988; Bauder and Brock 2001; Nunes et al. 2007). Subjecting irrigation water to magnetic fields alters the physical and electromagnetic properties of water (Otsuka and Ozeki 2006) and can also influence soil chemistry. Magnetic treatment of irrigation water has led to increased leaching of dissolved minerals from soils when compared to non-magnetically treated water, with the largest effect observed for calcium (Ca), magnesium (Mg), and phosphorus (P) (Noran, Shani, and Lin 1995). This effect is also utilized in industrial systems to reduce scale buildup in heat exchangers (Ambashta and Sillanpää 2010; Gabrielli et al. 2001). The increased leaching of soil Ca, Mg, and P from irrigating with magnetically treated water was attributed to the alteration in solubilities of precipitates due to the interaction of the magnetic field on water molecule properties (Otsuka and Ozeki 2006). For example, magnetic treatment was found to alter surface tension of water (Amiri and Dadkhah 2006; Chibowski,

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Table 1. Selected properties of soil (0–15-cm depth).

Sand	Silt[a]	Clay[a]	EC[‡]	pH[‡]	CEC[‡]	$CaCO_3$[§]	OC[§]	C[¶]	N[¶]	C:N
– – – – g kg^{-1} – – – –			dS m^{-1}		mol_c kg^{-1}	%	– – – – g kg^{-1} – – – –			
220	600	180	0.47	8.1	0.21	27	5.1	32.4	0.7	44.0

[a]Particle size analysis: hydrometer method applied after removal of organic matter.
[‡]Electrical conductivity (EC) and pH was determined on a saturated extract of the soil; CEC = cation exchange capacity.
[§]Calcium carbonate equivalent ($CaCO_3$) was determined using a pressure-calcimeter (Sherrod et al. 2002). Organic carbon (OC) was determined by dry combustion after pretreatment to remove inorganic carbon (Shimadzu Total Carbon Analyzer).
[¶]Soil total carbon (C) and total nitrogen (N) were determined on a freeze-dried sample with a Thermo-Finnigan FlashEA1112 CN analyzer (CE Elantech Inc., Lakewood, NJ)

Szcześ, and Hołysz 2018). Additionally, this increased leaching has also been attributed to the breaking of the molecular arrangement of water by the magnetic field, through the destruction of water microstructure and clusters (Chebotareva, Nanieva, and Remez 2020). The presence of dissolved salts and oxygen also increases the effect of the magnetic field on water's properties alteration (Otsuka and Ozeki 2006). However, these effects are finite in temporal duration (Chebotareva, Nanieva, and Remez 2020; Coey and Cass 2000).

Additional treatment methods could also alter the physical and electromagnetic properties of water. Lentz (2022) showed that the influence of mineralized irrigation water on soil chemistry can be altered via its physical manipulation prior to soil application. When irrigation water subjected to turbulent- flow preconditioning was applied to an incubated, calcareous soil for four to eight weeks, it changed the chemical composition of soil leachate, and consistently increasing mean concentrations of potassium (K), ammonium nitrogen (NH_4-N), Mg, and Ca by 1.2- to 1.4-fold compared to untreated water (2022). Notably, this increase in Ca and Mg is very similar to the results observed for magnetically treated water (Noran, Shani, and Lin 1995). However, little is known about the long-term effects of turbulent-flow conditioning on the quality of leachate water, soil nutrient status, or nutrient uptake by crops. Research described herein was designed to address this knowledge gap. We applied either turbulent-conditioned or untreated irrigation water to a degraded silt loam soil and measured crop yields, soil nutrient leaching, and nutrient availability in the following 5 to 9 years.

Materials and methods

We collected soil from the 0- to 15-cm depth in an eroded Portneuf silt loam (coarse-silty, mixed superactive, mesic Durinodic Xeric Haplocalcids) near Kimberly, ID (42°31′N, 114°22′W, 1190 m elevation). The soil was strongly calcareous due to topsoil loss, which had exposed the Bk horizon (Robbins, Mackey, and Freeborn 1997). The material was air dried, sieved through a screen having 4.7-mm by 12-mm perforations, and mixed thoroughly with a shovel. Soil particle size analysis was determined via the hydrometer method, applied after the removal of organic matter (Gee and Orr 2002). Soil total carbon (TC) and total nitrogen (TN) were determined on a freeze-dried sample with a Thermo-Finnigan FlashEA1112 CN analyzer (CE Elantech Inc., Lakewood, NJ), total inorganic carbon (TIC) was determined using a pressure-calcimeter procedure (Sherrod et al. 2002), and total organic carbon (TOC) by difference. The soil electrical conductivity (EC) and pH were determined on a saturated-paste extract (Rhoades 1996; Thomas 1996). Soil properties are reported in Table 1. The soil's coarse clay fraction (e.g., McDole and Maxwell 1966) is dominated by weathered or hydrous mica (50–60%) and includes 10–20% kaolinite and 10–15% montmorillonite (McDole and Maxwell 1966).

Instead of using distilled water to irrigate soils in the experiment, we used tap water because its chemistry more closely matched that of local irrigation water and did not require the construction of a separate pressurized water supply. For one treatment, the tap water was preconditioned via turbulent flow before it was applied to the soil. The turbulent-flow-inducer, water conditioning device employed tap water under typical domestic water pressures. The cylindrical device directed water flow through a series of spherically diverging and converging pathways to induce highly turbulent flow (2022).

Experimental design

The experimental design was completely randomized with four replicates. The design comprised two irrigation treatments: irrigation using either unconditioned tap water (Tap) or turbulent-flow conditioned tap water (CTap). The experiment was established in the 2009 crop year and continued through the 2017 growing season. A soil filled, 14-L, 26-cm-diam. x 26-cm-deep planting pot comprised each experimental unit. Pots were prepared by lining the bottom with weed barrier cloth followed by a base-layer of approximately 5-cm of wet sand. Each pot was then filled with 13.2 kg of Portneuf soil, which was packed to a nominal dry bulk density of 1.4 g cm^{-3} by firmly tapping the vessel on the concrete floor five times.

Potted soils were prepared over a period of several weeks beginning in late spring. After preparation, each pot was fertilized (Table 2) and kept moist in a greenhouse until 2 July 2009, when they were moved outdoors to start the current study. Pots remained outdoors except for 3–4 days each spring when they were moved under cover to perform leaching measurements (described below). All other sampling and measurements were conducted outdoors. Pots were arranged in a shallow trench with straw packing around pot sidewalls to insulate them from surface heating/cooling effects (Fig. S1). The straw was replaced by bark-chip mulch in subsequent years. A series of locally cultivated crops were grown in pot soils from 2009 through 2017 to simulate farm conditions (Table 2). We could not duplicate local rotations because the pots did not lend themselves well to root crops or silage corn (although one sweet corn crop was included). Because conventional tillage is a common practice in this area of the US, the pots were manually tilled each spring to simulate annual tillage; soils to a 15-cm depth were inverted and mixed using a shovel. Crop planting, harvest information and soil sampling dates are reported in Table 2.

An automated flow-emitter system supplied an equal volume irrigation water (±13%) to all pots to meet estimated crop evapotranspiration requirements (Fig. S1). The irrigation water pumped from groundwater via our pressurized laboratory system had an average EC of 0.80 dS m^{-1}, pH of 7.3, and mean concentrations (mg L^{-1}) of Ca = 55, K = 4.8, Mg = 29, sodium (Na) = 59, sulfur (S) = 22, chloride (Cl) = 27, nitrate nitrogen (NO_3-N) = 4.5, NH_4-N = 0.12, and P = .07. A sprinkler timer/controller unit scheduled water applications of 2 to 5 min once or twice daily depending on need. The emitter nozzles,

Table 2. The type and number of crop plants grown, ammonium nitrate (NH_4NO_3), potassium dihydrogen phosphate (KH_2PO_4) and potassium chloride (KCl) fertilizer applied and date, and dates of planting, harvest, and soil sampling during each year of the study.

Year	Crop	N as NH_4NO_3	P_2O_5 as KH_2PO_4	K_2O as KH_2PO_4, KCl	Fertilizers applied	Planting date	Number of plants per pot†	Harvest date	Date soil sampled
		– – – – (kg ha^{-1}) – – – –							
2009	Bean (*Phaseolus vulgaris L.)*	100	22.4	59.6	23 Apr ‡	6 Jul ‡	2	30 Sep	17 Apr ‡
2010	Barley (*Hordeum vulgare L.)*	277‡	-	-	18 May	14 May	11	3 Aug	19 Apr
2011	Pea (*Pisum sativum*)	-	-	-	-	17 May	2	2 Aug	11 May
2012	Bean (*Phaseolus vulgaris L.)*	-	-	-	-	1 Jun	4	14 Sep	4 May
2013	Sweet Corn (*Zea Mays L.)*	200	22.4	37.2	27Jun§ 12 Jul	31 May	1	22 Aug	10 May
2014	Barley (*Hordeum vulgare L.)*	50	5.6	9.3	1 Apr	19 May	2	31 Jul	5 May
2015	Bean (*Phaseolus vulgaris L.)*	-	-	-	-	19 May	4	21 Sep	5 May
2016	Pea (*Pisum sativum*)	-	-	-	-	18 May	4	-	3 May
2017	Oat (*Avena* sativa)	100	22.4	8.9	15 May	5 May	5	9 Aug	2 May

†For each crop, surplus seeds were planted and the seedlings were later thinned to this target number.
‡In 2009, the late-added topsoil pots were prepared and sampled on 28 July, planted on 29 July, and the 1st leaching was after harvest.
§Split application

with 1-mm diameter outlets, produced a mean flow of 100 mL min^{-1}. The irrigation system was altered in early June 2014 by adding a 15-psi pressure regulator to both the Tap and CTap irrigation lines (Fig. S1). These devices simplified water flow rate adjustments. At harvest, the entire above-ground crop tissue was removed from each pot. The crop roots remained in pot soils except for the corn root crown, which was removed at planting the following year. Pot surface soils were left fallow and uncovered during the non-growing season.

Nutrient leaching losses

Nutrient losses in soil drainage water were evaluated by leaching the pot soils prior to planting each spring, between mid-April and the first week of May from 2010 to 2017. In addition, a "fall" leaching event was conducted each year between mid-Sep. and mid-Dec. from 2009 to 2013. Initiation of drainage typically required the application of >25 mm water, and because irrigation and precipitation events rarely exceeded that volume, little leaching likely occurred during other times of the year. The one exception occurred on 6 Aug. 2014, when a thunderstorm produced a rare 51-mm rainfall.

Just prior to leaching, the pots were moved to a covered location and placed on individual collection devices that funneled seepage water from pot drains into 2.4-L, foil-capped, glass bottles. Where necessary, we compressed surface soil against pot sidewalls to prevent bypass flow. For most leaching events, we collected between 600- and 850-mL of leachate, varying with year. Treatment-appropriate irrigation water was added in 250 to 700-mL portions over 12 to 24 hours until drainage began. The portions of added water were reduced as the volume of leachate collected approached the target value. The pots were moved back outdoors after completing the leaching procedure. During each leaching event, we applied nearly equal input water volumes to each pot. We thoroughly mixed collected leachate samples, a subsample was collected for pH and EC determinations, and a second subsample was filtered through a < 45-micron Millipore membrane, stabilized with a saturated boric acid (H_3BO_3) solution (1 mL per 100-mL sample), and stored at 4°C. Filtered samples were analyzed by the following: an automatic, colorimetric flow injection analyzer (Lachat Instruments, Loveland, Co) determined concentrations of NO_3-N, NH_4-N and Cl; ICP-OES determined Ca, K, Mg, Na, P, S, iron (Fe), zinc (Zn), manganese (Mn), and aluminum (Al) (PerkinElmer Optima 8300, American Fork, Utah); and a Shimadzu TOC-5050A instrument (Shimadzu Scientific Instruments, Columbia, MD) measured dissolved organic carbon (DOC, as non-purgeable organic carbon).

Soil nutrients, crop yield, and nutrient uptake

Soil and plant sampling and protocols used to measure soil chemical status and nutrient uptake in above-ground crop tissue are identical to those reported by Lentz and Ippolito (2021) and are summarized here. We collected soil samples from pots (0 to 15-cm depth) prior to planting each year (2010 to 2017) and determined: soil EC and pH; NO_3-N and NH_4-N (2 M potassium chloride extract); Olsen-P; available K, Na, Mg, Zn, Mn, copper (Cu), and Fe (diethylenetriaminepe-nataacetic acid [DTPA] extract); TC, TN, and TIC. From 2009 through 2013, plant yields were measured, and above-ground biomass collected and analyzed for total C, N, Ca, K, Mg, Na, P, S, Fe, Zn, Mn, and Al.

Calculations and statistical analysis

A multivariate methodology assessed the separation of treatment responses in a multidimensional space using SAS version 9.4 (Institute Inc 2012). It tested for overall water-treatment effects on all components in each data set (soil nutrient properties, plant nutrient uptake, and leachate mass losses). Each analysis included four steps: *i*) A stepwise discriminant analysis (SAS-PROC StepDisc) identified the subset of parameters that best discriminated between the two water treatment classes; *ii*) This parameter subset was employed in an overall one-way multivariate analysis of variance (MANOVA) using Wilk's likelihood ratio to test equality of mean vectors between classes. The procedure used SAS-PROC GLM where the MODEL was defined as "[parameter subset] = water treatment," and MANOVA tested the water treatment effect hypothesis with the residual matrix as the error; *iii*) If the hypothesis test was significant, simultaneous Bonferroni's confidence intervals were computed to investigate between-group separations (in multidimensional space) for included variables (Srivastava and Carter 1983); and *iiii*) Pearson Correlations computed by SAS-PROC CORR evaluated relationships of the parameter subset with other parameters.

In addition, a univariate (one-dimensional) approach analyzed individual soil nutrient properties and leachate mass losses separately by year using ANOVA and SAS-PROC MIXED (no random effect specified) and 95% confidence limits were computed to evaluate Tap vs. CTap mean separations. Similar analyses were used to examine responses that were averaged across years (soil nutrient properties, plant nutrient uptake) and values that were summed across years (leaching mass losses). It is important to note that cumulative leachate mass-loss responses were summed across all spring and fall leaching events. Where needed to resolve nonconstant variance or improve distribution, responses were transformed prior to analysis, primarily using common logs, and means were back-transformed to original units for reporting. Statistical analyses were conducted using a significance probability (P) of 0.05.

Results

Nutrient leaching

Leachate volumes for Tap and CTap were similar in each of the eight annual spring leaching events except one. In 2014, the mean volume leached from CTap pots was 10% greater than that for Tap (Fig. S2). However, the difference did not appear to consistently influence leachate mass-loss values in 2014, confirming that treatment responses primarily originated from differences in associated leachate concentrations (Figures 1 and 2).

Leaching mass losses of the K, NH_4-N, Na, and Cl components were selected by discriminant analysis as best differentiating between water treatments, and MANOVA results indicated that the associated group mean vectors differed with water treatment (Table 3). Two of the four nutrient components comprising the group vectors were influenced by water treatment; CTap increased leaching mass losses of K 1.7-fold and Cl 1.5-fold compared to Tap. When selecting parameters, discriminant analysis controlled for the variation accounted for by any variables already included in the model. Therefore, any unselected parameters may also have been influenced by the treatments if they shared correlations with the selected parameters (Table S1). Thus, the effects of CTap on leachate were further clarified when we examined mass losses that were summed across each spring and fall leaching event in all years. Compared to Tap water, CTap increased cumulative NO_3-N mass losses 2.5-fold, Mn 2-fold, K 1.6-fold, Mg, DOC, and NH_4-N an average 1.2-fold, and increased the mean EC of leachate 1.2-fold (Table 4). Note that cumulative values accentuated treatment differences in many cases; the influence of CTap on fall nutrient losses appear greater than that of spring because mean leaching mass losses for Ca, Na, K, NH_4N were 1.6-fold greater, and Cl was 3.7-fold greater for fall events compared to that of spring ($P < .017$). And as observed for spring leaching events, the average leachate volume across all spring and fall events did not differ among treatments (Table 4).

The annual leaching mass-losses data indicate that treatment effects on nutrient losses each spring sometimes differed from year to year (Figures 1 and 2). Generally, Tap and CTap waters both produced grossly similar mass-loss patterns over time for a given component. For example, K, Na, P, and Cl losses trended downward while NH_4-N losses trended upward during the period. The pattern of annual leaching losses for Ca, Mg, Na, NO_3-N, S, and leachate EC were similar overall even to the extent of including a distinctive peak in 2014. Leaching losses for Ca, Mg, Na, NO_3-N, leachate EC, and Cl were moderately, positively correlated with fertilizer applications, whereas K, P, S, and NH_4-N were not (Table S2).

Spring leaching mass losses for Tap relative to the CTap treatment generally followed a similar pattern for measured components: CTap values were greater than or equal to those of Tap each year, and CTap more consistently increased K, NH_4-N, and Cl mass losses during the period (Figures 1 and 2). Results for pH differed from those of other parameters in that CTap-leachate mean pH values were less than or equal to those of Tap (Figure 2f). Finally, note that mean differences between Tap and CTap mass losses for K, Ca, NO_3-N, NH_4-N, and EC trend to a minimum value in the years after 2014 (Figure 1a, c, e, f; Figure 2a).

Soil nutrient properties

From all soil properties, stepwise discriminant analysis selected TIC, Cu, K, and Olsen P that best differentiated between water treatments and MANOVA results were highly significant, indicating that mean vectors defined by the selected parameters differed due to water treatment (Table 3). Between-

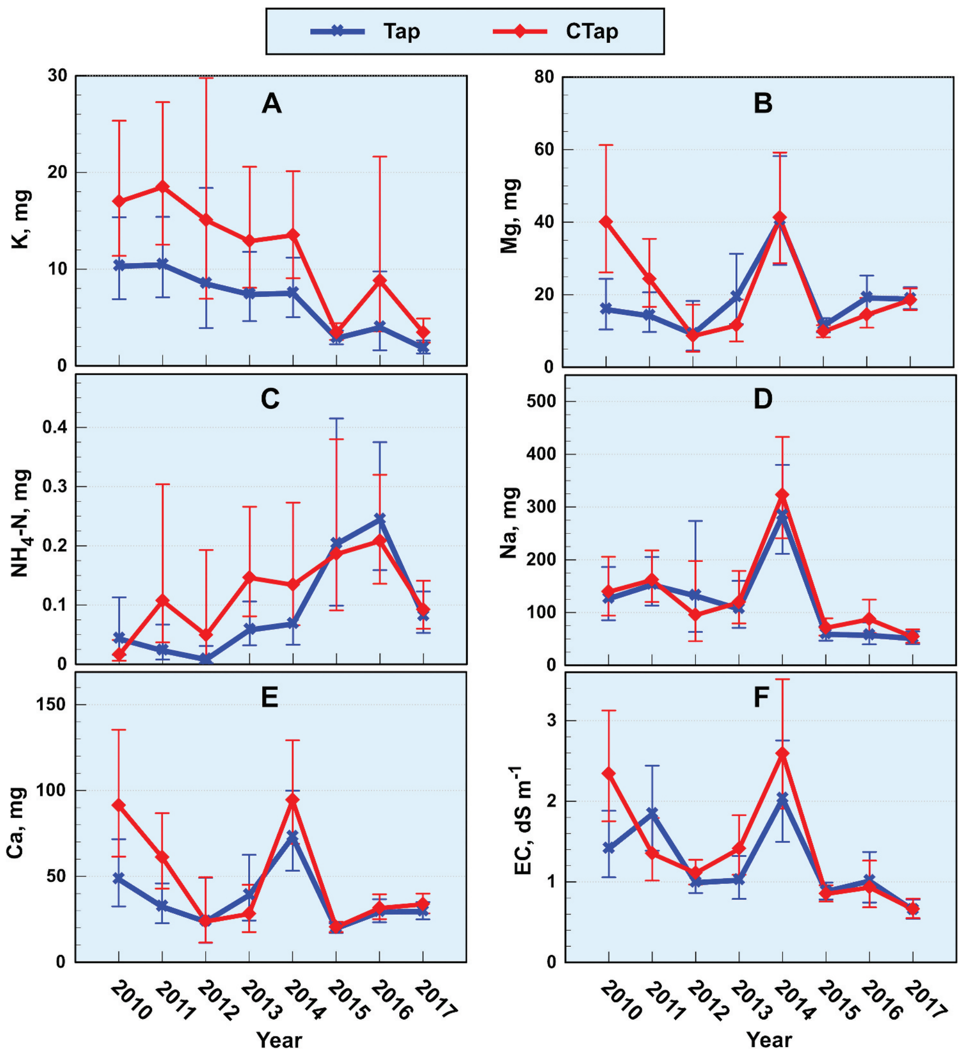

Figure 1. Treatment and year effects on percolation mass losses during spring leaching events, K (a), Mg (b), NH4-N (c), Na (d), Ca (e), and leachate electrical conductivity, EC (f). Symbols represent back-transformed means of mass losses and error bars represent 95% confidence limits on the means (n = 4).

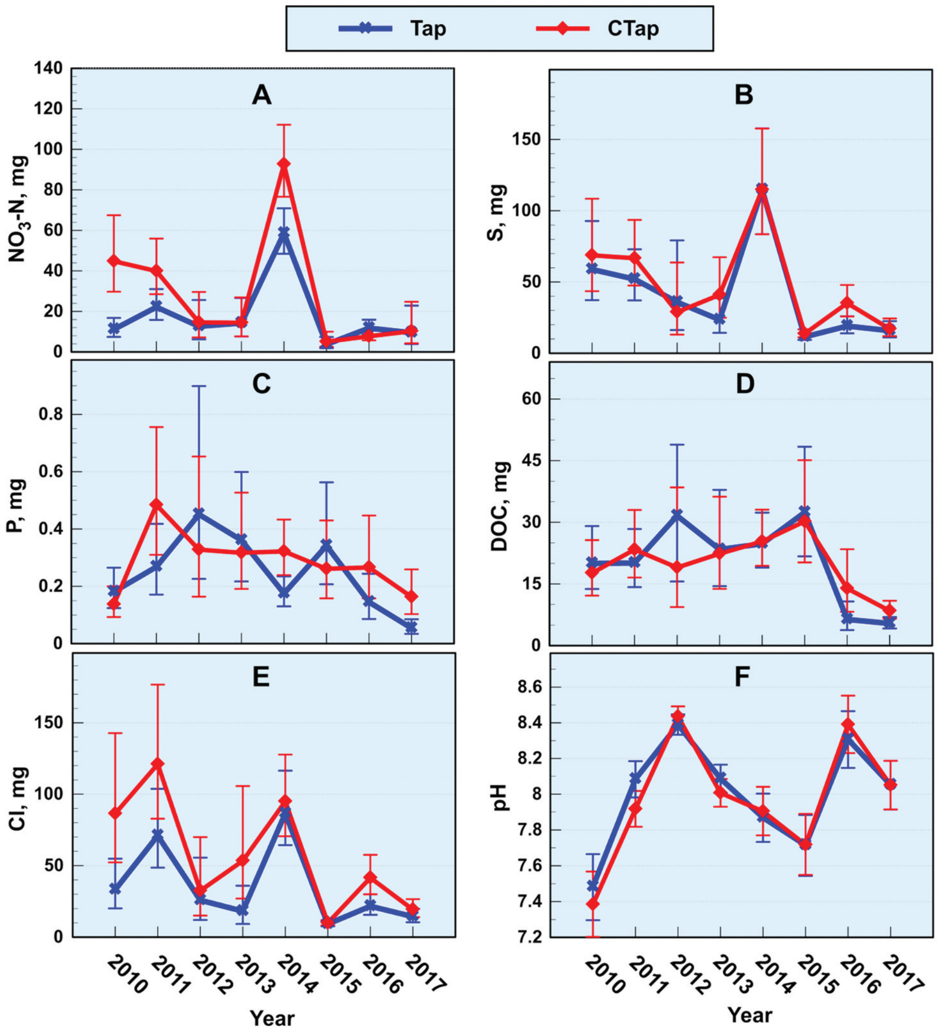

Figure 2. Treatment and year effects on percolation mass losses during spring leaching events, NO3-N (a), S (b), P (c), dissolved organic C, DOC (d), Cl (e), and leachate pH (f). Symbols represent back-transformed means of mass losses and error bars represent 95% confidence limits on the means (n = 4).

group mean comparisons showed that CTap water increased soil Cu, K, and Olsen P 1.4-fold, and decreased TIC 8% relative to Tap (Table 3). When the overall average soil property responses were analyzed for each parameter individually, results showed that water treatment influenced soil nutrient properties other than those selected in the discriminant analysis. Namely, CTap increased average soil Zn 2.4-fold, Na and Fe 1.2-fold, and decreased soil TC (4%) and Mg (9%) relative to the Tap water (Table 5).

The annual soil data indicate that, with the exception Cu, and Fe, treatment by year interactions were significant ($P < .03$), i.e., treatment effects on measured soil properties differed depending on the year (Figures 3 and 4). The year-by-treatment responses showed that: 1) CTap soil Fe mean values exceeded that of Tap in 7 of 8 years and the difference was significant in 4 out of 8 (Figure 4e); 2) in general, CTap's effects on K Mg, Olsen P, TC, TIC, Cu, and Zn were consistent across the years (Figures 3 and 4); 3) CTap's influence on Zn declined with time but increased with time for Cu (Figure 4c,d); and 4) CTap soil pH values decreased relative to Tap in the first 3 years but equaled or exceeded Tap values in succeeding years (Figure 4g).

Table 3. Multivariate results for each data set: mean values for parameters selected by discriminate analysis on water treatments. Results of overall one-way manova testing for the equality of mean vectors using Wilk's likelihood ratio, and between-group mean comparisons for specific parameters derived from Bonferroni-adjusted confidence intervals on the means.

Leaching mass losses, mg			Soil properties, mg kg^{-1}			Plant uptake, mg kg^{-1}		
	Treatment †			Treatment †			Treatment †	
Parameter	Tap	CTap	Parameter	Tap	CTap	Parameter	Tap	CTap
K	5.66 b	9.81 a	TIC (%)	2.82 a	2.60 b	Zn	25.1 b	44.7 a
NH_4-N	0.06	0.09	Cu	1.04 b ‡	1.46 a	Na	1034	949
Na	103	113	K	36.8 b	52.2 a	TC	39.8	39.0
Cl	26.9 b	39.1 a	Olsen P	18.3 b	25.0 a			
MANOVA	$P = .001$		MANOVA	$P < .0001$		MANOVA	$P < .0001$	

†Tap = tap water; CTap = conditioned tap water
‡For each data set, water treatment means followed by the same letter are not significantly different ($P < 0.0125$, which includes the Bonferroni adjustment = 0.05/4). No letters are listed if the comparison was not significant.
§Wilk's lambda tests hypothesis that group mean vectors for Tap and CTap treatments are equivalent.

Biomass yield and nutrient uptake

Biomass yields did not differ between Tap and CTap pots in three of the five years it was measured ($P > .4$, Table S3). However, the CTap barley biomass yields were 25% smaller than Tap in 2010 ($P = .006$) and CTap pea biomass yields were 48% smaller in 2011 ($P = .0004$). The five-year mean biomass yields did not differ between Tap and CTap (Table 6).

Discriminant analysis of annual elemental concentrations in aboveground biomass selected Zn, Na, and TC as those that best differentiated between treatment classes (Table 3). The significant MANOVA results indicated that mean vectors defined by the selected parameters differed due to water treatment. Of the three parameters, the Bonferroni-adjusted comparisons confirmed a treatment effect for Zn; CTap increased Zn uptake 1.4-fold compared to Tap (Table 3). The analyses of individual elements revealed further treatment effects; CTap increased biomass element concentrations for Al and Fe an average 1.3-fold, increased TN, Ca, K, and S by 1.1-fold and decreased TC 2% relative to Tap (Table 6). However, the treatment effect on total element uptake in all biomass (5-year, cumulative elemental uptake per unit area) revealed different relationships; CTap had increased total Zn 1.3-fold and decreased Na by 25%, S by 17%, and Mg by 15% on average relative to Tap (Table 6). The reduced cumulative uptake for these elements in CTap pots were primarily due to the large decrease in CTap biomass relative to Tap in 2010 and 2011 (Table S3).

Table 4. Tap water (Tap) and conditioned tap water (CTap) effects on cumulative leachate volume, cumulative nutrient mass losses, and pH and EC computed across all leaching events and years. Values are arithmetic means total losses summed across both spring and fall leaching events performed from 2009 to 2017 (n= 4).

Treatment	Tap	CTap
Drain vol. (L)	8.92 †	9.02
Na (g)	2.19	2.11
Ca (mg)	761 b	862 a
K (mg)	121 b	188 a
Mg (mg)	306 b	350 a
P (mg)	3.13 b	3.60 a
S (mg)	923	970
NO_3-N (mg)	240 b	605 a
NH_4-N (mg)	1.73 b	2.25 a
Cl (g)	1.42	1.59
DOC (mg)	266	284
Fe (mg)	0.19	0.29
Zn (mg)	0.10	0.07
Mn (mg)	0.02 b	0.04 a
Al (mg)	0.28	0.25
pH	8.00	7.98
EC (dS m^{-1})	1.37 b	1.62 a

†For each response category, means followed by the same letter are not significantly different ($P < 0.05$).

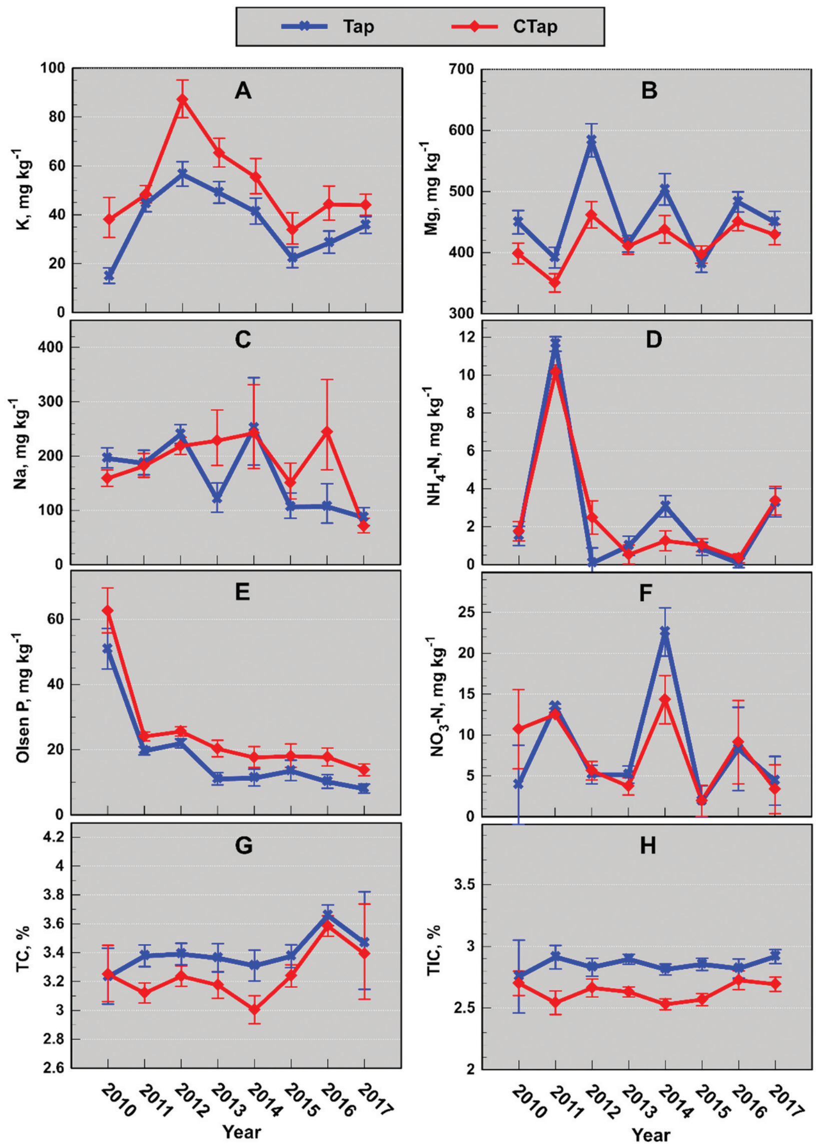

Figure 3. Treatment and year effects on DTPA extractable soil K (a), Mg (b), Na (c), soil NH4-N (d), Olsen P (e), NO3-N (f), total C, TC (g), and total inorganic C, TIC (h). Symbols represent back-transformed means of soil samples collected in spring each year from 2010 to 2017 and error bars represent 95% confidence limits on the means (n = 4).

Discussion

Leachate

The multivariate discriminant analysis of leached mass losses and univariate ANOVA tests on each cumulative component loss response present clear evidence that CTap water increased leaching of select soil cations and anions relative to Tap, likely leading to CTap increasing leachate EC as compared to Tap (Tables 3 and 4). These results are comparable to those of the companion soil column study where soils treatments were applied for at least six or eight weeks (2022). Furthermore, in both the current and companion study, K, NH_4-N, and Mg were leachate components most consistently selected by multivariate analysis as best discriminating between water treatments (2022). This may suggest that soil K, NH_4-N, and Mg components were most directly influenced by the CTap treatment. In contrast, anionic

Table 5. Tap water (Tap) and conditioned tap water (CTap) effects on individual soil property components. Values are averages of soil samples collected in spring each year from 2010 to 2017 (*n*= 4).

Treatment	Tap	CTap
TC† (%)	3.39 a‡	3.25 b
TIC† (%)	2.82 a	2.60 b
TOC† (%)	0.58	0.65
TN† (%)	0.07	0.07
Olsen P (mg/kg)	18.3 b	25.0 a
NO_3-N (mg/kg)	8.11	7.66
NH_4-N (mg/kg)	1.71	1.93
DTPA K (mg/kg) §	33.8 b	49.8 a
DTPA Mg (mg/kg)	457 a	417 b
DTPA Na (mg/kg)	138 b	159 a
DTPA Fe (mg/kg)	3.01 b	3.55 a
DTPA Zn (mg/kg)	1.05 b	2.47 a
DTPA Mn (mg/kg)	5.23	5.21
DTPA Cu (mg/kg)	1.04 b	1.46 a
pH	7.94	7.96
EC (dS m^{-1})	0.45	0.49

†TC = total carbon; TIC = total inorganic C; TOC = total inorganic C; TN = total nitrogen.
‡Treatment means followed by the same letter are not significantly different ($P < 0.05$).
No letters are shown if treatment values were not significantly different.
§DTPA = Diethylenetriaminepenataacetic acid extraction.

components were less consistently selected as discriminating (Cl in the current study vs. DOC in the companion study), suggesting that anion leaching was indirectly influenced by CTap through electrical neutrality effects, where mass losses were controlled by the availability of anionic species. The greater ionic concentrations in the CTap soil solution/leachate might result from CTap water's lower surface tension (2022), potentially from mechanical assisted breaking of water microstructures, leading to more complete wetting/filling and draining of soil pores, greater dissolution of soil constituents, and a relative increase in component leaching losses (Bachmann and van der Ploeg 2002; Karkare and Fort 1993; Kim et al. 2004; Smith and Gillham 1999). Furthermore, the surface tension of the soil solution in CTap pots may have decreased further relative to Tap because of the greater availability of Na in CTap soils (Table 5). Soil-derived organics entrained in infiltrating water decrease surface tension of the soil solution and the increased exchangeable Na in CTap can amplify this surface tension depression via dispersion effects (Tschapek, Scoppa, and Wasowski 1978).

The convergence of Tap and CTap mean mass-loss values for K, NH_4-N, Ca, EC and NO_3-N after 2014 (Figure 1a, c, e, f; Figure 2a) could be explained in two ways. First, a ready supply of excess ions or elements may have been depleted in the CTap soils over time due to increased leaching losses. Second, the pressure regulators installed in the irrigation system in 2014 may have introduced enough turbulence into the Tap water flow to eliminate conditioning differences between the two treatments. Since it is unlikely that the source of all the associated soil constituents would become limiting at precisely the same time, we concluded that the 2014 installation of pressure regulators had effectively neutralized treatment differences in subsequent years.

The annual pattern exhibited by leachate pH varied by up to 1.0 pH unit during the 9-y period (Figure 2f). We attributed this to annual changes in added potassium dihydrogen phosphate (KH_2PO_4) and ammonium nitrate (NH_4NO_3) fertilizers, tempered by annual fluctuations in spring precipitation and temperature conditions and crop uptake. The acidic nature of KH_2PO_4 and acidification associated with increased soil nitrification combined to reduce soil pH (Mengel and Kirkby 1982; Sample, Soper, and Racz 1980; Thomson, Marschner, and Römheld 1993). The peak in leachate mass losses and leachate EC observed in 2014 resulted because this leaching event uniquely occurred just 3-weeks after fertilizers had been applied to the soils.

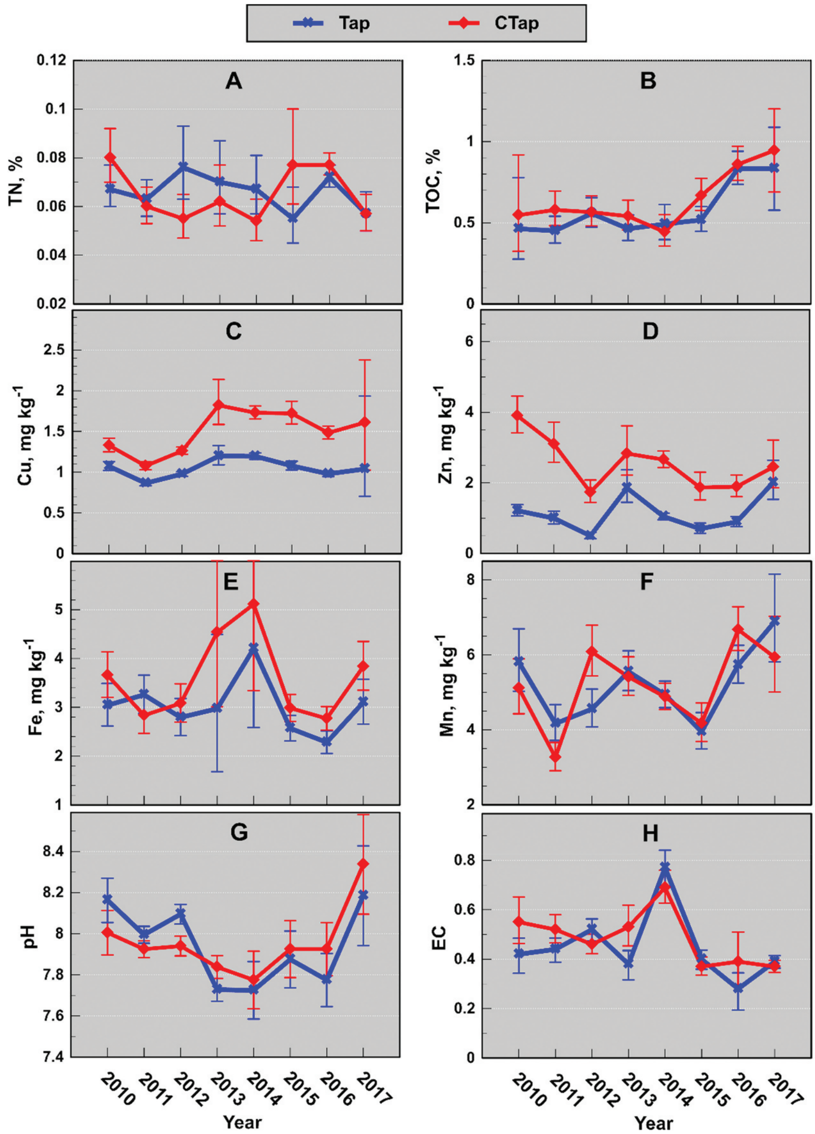

Figure 4. Treatment and year effects on soil total N, TN (a), total organic C, TOC (b), DTPA extractable soil Cu (c), Zn (d), Fe (e), Mn (f), soil pH (g), and electrical conductivity, EC (h). Symbols represent back-transformed means of soil samples collected in spring each year from 2010 to 2017 and error bars represent 95% confidence limits on the means (n = 4).

Soil properties

The reduced soil TIC and TC in CTap soils, which developed after two irrigation seasons, suggests that CTap increased the loss of inorganic carbon relative to Tap soils (Tables 3 and 5). This could have occurred via an increase in the loss of HCO_3 in leachate or of CO_2 to the atmosphere. The former could result from an increased weathering of calcium or magnesium carbonates, $CaCO_3 + CO_2 + H_2O \rightarrow Ca(HCO_3)_2$. Increased flux of CO_2 gas from water may result from increased vaporization and degassing of aqueous CO_2 in response decreased water surface tension (Beruto et al. 2003) or the dissolution of carbonates in reaction with hydrogen ions, $CaCO_3 + 2\ H^+ \rightarrow Ca_2 + CO_2 + H_2O$ (Mengel and Kirkby 1982; Monger et al. 2015). Recent research reported that turbulent water streams produce unexpectedly large fluxes of CO_2 (Horgby et al. 2019).

Table 6. Tap water (Tap) and conditioned tap water (CTap) effects on overall average biomass yield and element concentration in biomass, and cumulative biomass and elemental uptake summed across years 2009 to 2013 (n= 4).

	Mean uptake ‡			Cumulative uptake §		
Treatment	Units	Tap	CTap	Units	Tap	CTap
Biomass	g pot^{-1}	21.1 †	19.4	(Mg/ha)	35.0	31.4
TC	%	39.9 a	39.1 b	(Mg/ha)	13.6	12.4
TN	%	1.79 b	1.98 a	(Mg/ha)	0.476	0.455
Ca	g kg^{-1}	6.4 b	7.3 a	(kg/ha)	150	156
K	g kg^{-1}	18.0 b	20.2 a	(kg/ha)	588	541
Mg	g kg^{-1}	4.12	4.16	(kg/ha)	109 a	93.0 b
Na	g kg^{-1}	1.03	0.95	(kg/ha)	53.3 a	40.3 b
P	g kg^{-1}	2.34	2.42	(kg/ha)	64.2	54.1
S	g kg^{-1}	1.32 b	1.44 a	(kg/ha)	41.0 a	33.9 b
Fe	mg kg^{-1}	77.4 b	95.0 a	(kg/ha)	2.10	2.33
Zn	mg kg^{-1}	25.1 b	36.0 a	(kg/ha)	0.86 b	1.09 a
Mn	mg kg^{-1}	35.0	33.8	(kg/ha)	1.33	1.16
Al	mg kg^{-1}	81.4 b	103 a	(kg/ha)	2.23	2.64

†For each treatment category, means followed by the same letter are not significantly different (P < 0.05). No letters are shown if treatment values were not significantly different.
‡Values are geometric means, biomass element concentrations are given per unit mass of dry matter.
§Values are arithmetic means, cumulative uptake is given as elemental mass per unit area.

The greater nitrate concentration in CTap soil solution relative to Tap (Figure 2a and Table 4) suggests greater nitrification rates, which could have increased H^+ concentrations and subsequently led to additional carbonate dissolution (Mengel and Kirkby 1982). Both reactions would increase Ca ions in the soil solution and displace Mg, K, and NH_4 from soil exchange sites. This is consistent with increase in Ca, Mg, K and NH_4 in the soil solution of CTap compared to Tap (Table 4).

Soil Olsen P may have increased in CTap relative to Tap soils due to release of absorbed P from solubilized $CaCO_3$. Olsen P was negatively correlated with leachate pH and positively correlated with spring leachate Ca, K, and NH_4-N loads, and EC, which support this hypothesis (Table S2). Slightly lowering soil pH can lead to enhanced dissolution of sparingly soluble Ca-P mineral phases (Hinsinger and Gilkes 1995; Zhan et al. 2015).

CTap's apparent boost of soil Zn, Fe, and Cu availability (Table 5) doesn't appear to be related to a pH effect since their correlations with soil or leachate pH were slight or nonexistent. Zinc alone was significantly but only slightly, negatively correlated with leachate pH (coefficient = −0.29; P= .03) yet was most strongly and positively related with leachate Ca, K, Mg and Cl (Table S2). Solution Ca, K, and Mg cations increased in CTap soils relative to Tap, which may have facilitated their exchange with di- and trivalent metal ions from stable metal-organic matter complexes and the liberation of micronu-trient elements (Sample, Soper, and Racz 1980).

Increased soil TOC in 2016 and 2017 may be due to unusually warm springs in the preceding growing seasons, which encouraged biomass production, followed by unusually cold, wet winters, which dis-couraged biomass decomposition by heterotrophs. This was confirmed by the decrease in soil DOC leaching observed in 2016 and 2017 and supported by findings of Brooks, McKnight, and Bencala (1999).

Crop yield and nutrient uptake

It is not clear why CTap soils produced smaller biomass yields than Tap in 2010 and 2011. There were no notable effects on elemental uptake in those two years that might explain the outcome. The treatments may have responded differently to the unusually cool and wet spring conditions that prevailed in those years, especially considering that the crops were planted relatively early compared to other years (Fig. S3, Table 2). Possibly, the increased wetting potential of CTap irrigation water (2022) exacerbated effects of the cool wet spring on early crop growth. The increased elemental concentra-tions in CTap crop biomass relative to that of Tap were attributed partly to CTap's lessor mean biomass production (Table 6) and the increased availability of nutrients in CTap soils (Table 5).

Comparison with companion study

The companion soil column study (Lentz, 2022) conducted two column leaching experiments using two independently collected samples of eroded Portneuf soil, while the current study used a third independently collected soil sample. When the soils from the three samplings were treated for ≥6 weeks, CTap consistently (3 of 3) increased leachate concentration and mass losses of K and Mg over that of Tap water and slightly less consistently (2 of 3) increased Ca, NH_4-N, NO_3-N, Mn, and EC (Lentz, 2022). In addition, the effect of CTap on K and NO_3-N in leachate relative to Tap increased as the treatment period increased from several weeks to several months; increasing from 1.3- to 1.7-fold for K and increasing from 1.2- to 2.5-fold for NO_3-N.

Uncertainty associated with the current study was greater than for column experiments because of *i*) challenges involved in thoroughly homogenizing the large volume of soil prior to distributing it to individual pots; *ii*) the greater potential for error applying irrigation water due to variable evapotranspiration rates among pots and the greater number of irrigation water applications; and *iii*) the additional unknown treatment interaction effects of rainwater inputs during the non-growing season. The extended treatment period of the current study presumably intensified treatment effects and helped to minimize effects of variability related to these uncertainties. Furthermore, when Tap irrigation water was subject to turbulent conditioning after 2014 from the installed pressure regulator, Tap-CTap treatment differences for several components trended to zero, giving additional evidence for the conditioning effect.

Conclusions

Results of the current study largely support those of a companion laboratory study (2022), showing that turbulent-flow-conditioned irrigation water (CTap) consistently increased leaching of K and Mg cations from a calcareous soil compared to untreated water (Tap). Leaching of other cations and anions also increased in response to CTap treatment, although these results were slightly less consistent across the two studies. The current study also provided evidence that CTap water increased the availability of some soil macro- and micro-nutrients and their uptake by crops. While effects were significant yet generally small, their long-term influences on soils and crops could be substantial. Further research is needed to determine if CTap effects can be confirmed for other soils and waters. If the capacity of this simple device to influence soil nutrient balance can be confirmed in broader applications, it could potentially provide an economical means of increasing the availability of nutrients in treated soils and managing or remediating degraded, salt-affected soils.

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Disclosure statement

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Does Turbulent-Flow Conditioning of Irrigation Water Influence Soil Chemical Processes: II. Long-Term Soil and Crop Study

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Supplemental Information (8 pages):

Tables S1 to S4

Figures S1 to S3

Table S1. Pearson correlation coefficients and significance for parameters selected by discriminant analysis for leaching mass loss responses with other leachate component mass losses (mg) and properties, EC (ds m^{-1}) and pH.

Nutrient properties of Leachate	Components selected by discriminant analysis †			
	K	NH_4-N	Na	Cl
DOC	0.67 ***	0.31***	0.75***	0.56***
NH_4-N	0.16	1	0.28**	0.43 ***
NO_3-N	0.60 ***	0.26*	0.64* **	0.73 ***
Ca	0.77 ***	0.36 ***	0.82 ***	0.89 ***
Na	0.81 ***	0.28 *	1	0.84 ***
Mg	0.71 ***	0.35 ***	0.78 ***	0.83 ***
K	1	0.16	0.81 ***	0.80 ***
Cl	0.80 ***	0.43 ***	0.84 ***	1
S	0.61 ***	0.26 **	0.59 ***	0.41 ***
P	0.49 ***	0.21 *	0.41 ***	0.24 *
EC	0.60 ***	0.25 **	0.68 ***	0.75 ***
pH	-0.36 ***	-0.14	-0.29 **	-0.46 ***
Al †	.	.	.	.
Fe †	.	.	.	.
Zn †	.	.	.	.
Mn †	.	.	.	.

*, $P \leq 0.05$ **, $P \leq 0.01$ ***, $P \leq 0.001$ ns, non significant

† Correlations not displayed if >30% of micronutrient concentration values fell below analytical detection limits.

Table S2. Pearson correlation coefficients and significance of soil property parameters and fertilizer applications (shaded cells) with spring leachate component mass losses or properties, EC (ds m^{-1}) and pH. Oval graphics highlight leachate components not correlated with fertilizer applications.

Soil	Leachate component mass loss or property †											
Variable	Ca	K	Mg	Na	P	S	NO_3-N	NH_4-N	Cl	DOC	EC	pH
TC	-.44 ***	-.27 *	-.29 *	-.48 ***	-.20	-.20	-.49 ***	0.15	-.44 **	-.39 **	-.42 ***	0.41 ***
TIC	-.20	-.10	-.15	-.03	-.02	.02	-.22	-.14	-.14	.17	.05	0.10
TOC	-.28 *	-.19	-.17	-.46 ***	-.21	-.21	-.32 *	-.27 *	-.33 **	-.51 ***	0.46 ***	-.33 **
TN	-.01	-.06	0.00	-.13	-.01	-.01	-.14	-.05	-.08	0.06	-.01	-.02
NO_3-N	0.62 ***	0.18	0.68 ***	0.69 ***	-.06	-.06	0.74 ***	-.14	0.70 ***	0.02	0.64 ***	-.02
NH_4-N	0.13	0.14	0.09	0.16	0.11	0.11	0.18	-.25 *	0.50 ***	-.03	0.18	-.02
Olsen P	0.41 ***	0.33 **	0.20	0.09	-.10	-.10	0.12	-.32 **	0.29 *	0.07	0.37 **	-.56 ***
Mg	-.10	-.13	-.03	0.11	-.09	-.09	-.01	-.14	-.22	-.03	-.07	0.45 ***
Na	0.24	0.39 **	0.12	0.69 ***	0.17	0.17	0.40 **	-.09	0.48 ***	0.43 ***	0.54 ***	0.16
K	0.03	0.36 **	-.04	0.18	0.27 *	0.27 *	0.19	-.14	0.24	0.11	0.08	0.51 ***
Zn	0.43 ***	0.36 **	0.35 **	0.09	-.07	-.07	0.30 *	-.08	0.39 **	-.14	0.25	-.29 *
Fe	0.36 **	0.02	0.35 **	0.54 ***	-.15	-.15	0.53 ***	-.11	0.36 **	0.09	0.43 ***	-.16
Mn	-.10	-.09	-.04	-.25 *	-.41 ***	-.41 ***	-.23	0.05	-.35 **	-.46 ***	-.23	0.28 *
Cu	0.12	0.05	0.11	0.10	-.12	-.12	0.16	0.28 *	0.01	0.02	-.05	-.09
pH	-.21	-.06	-.26 *	-.27 *	-.19	-.19	-.34 **	-.26 *	-.20	-.18	-.21	-.06
EC	0.61 ***	0.22	0.58 ***	0.79 ***	0.06	0.06	0.75 ***	-.22	0.63 ***	0.35 ***	0.70 ***	-.18
FN ‡	0.55 ***	0.20	0.48 ***	0.61 ***	0.11	0.11	0.64 ***	-.21	0.74 ***	0.23	0.59 ***	-.33 **
FP ‡	0.73 ***	0.07	0.69 ***	0.57 ***	-.23	-.23	0.64 ***	-.19	0.35 **	0.17	0.63 ***	-.67 ***
FK ‡	0.68 ***	0.10	0.60 ***	0.43 ***	-.26 *	-.26 *	0.50 ***	-.24	0.30 *	0.11	0.57 ***	-.72 ***

† Correlations not displayed if >30% of micronutrient concentration values fell below analytical detection limits.

‡ Fertilizer applied in the previous year: FN=as N; FP=as P_2O_5; FK=as K_20.

Table S3. Treatment and year effects on above-ground biomass. Values are arithmetic means (std. dev.) from biomass samples harvested from 2009 to 2013 (*n*=4).

	Year									
Treatment	2009		2010		2011		2012		2013	
	Biomass, Mg ha^{-1}									
Tap	1.06	(0.64)	10.59	(1.86)	2.25	(0.78)	3.80	(1.77)	17.33	(1.87)
CTap	1.34	(0.51)	7.92	(0.55)	1.12	(0.07)	4.55	(0.84)	16.50	(1.01)

Table S4. Pearson correlation coefficients and significance for soil property parameters selected by discriminant analysis with other soil components (mg kg^{-1}) and properties, EC (ds m^{-1}) and pH.

Soil nutrient	Soil components selected by discriminant analysis			
properties	Cu	K	TIC	Olsen P
TC	0.15	-0.28 *	0.88 **	-0.30 *
TIC	0.52 ***	-0.23	1	-0.02
TOC	-0.25 *	-0.09	-0.40 **	-0.27 *
TN	0.05	-0.23	0.24	0.19
Olsen P	-0.03	-0.12	-0.03	1
NO_3-N	0.12	0.08	0.10	-0.01
NH_4-N	0.28 *	0.06	-0.16	0.03
K	-0.26 *	1	-0.23	-0.12
Mg	0.15	0.14	0.24	-0.14
Na	0.09	-0.30 *	-0.17	-0.31 *
Fe	0.43 ***	-0.30 *	0.33 **	-0.14
Zn	0.53 ***	-0.18	0.56 ***	-0.19
Mn	-0.15	0.06	-0.04	-0.04
Cu	1	-0.26 *	0.52 ***	-0.03
pH	-0.05	-0.12	-0.28 *	0.23
EC	-0.19	0.25 *	-0.09	0.16

*, $P \leq 0.05$ **, $P \leq 0.01$ ***, $P \leq 0.001$ ns, non significant

Fig. S1

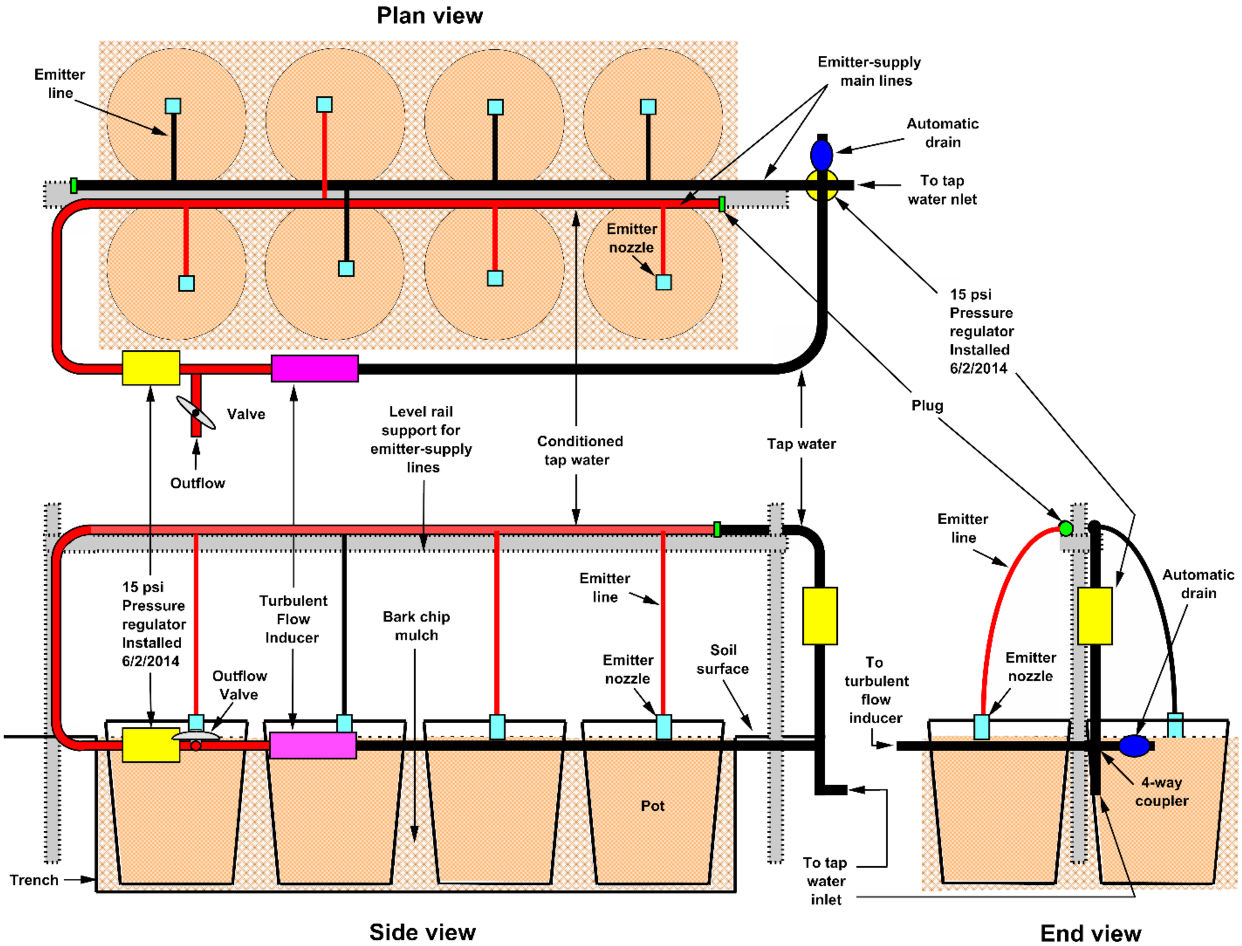

Fig. S1. The arrangement of pots in the outdoor soil trench and design of the automatic irrigation system.

FIG. S2

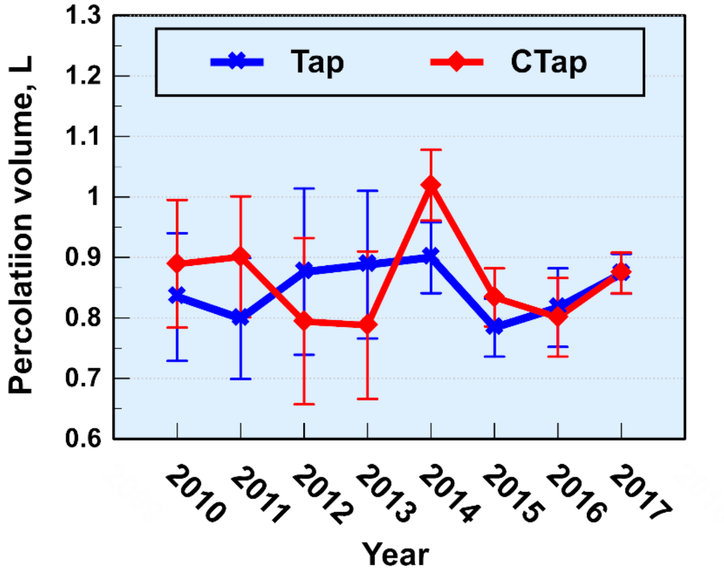

Fig. S2. Treatment and year effects on percolation volumes during spring leaching events. Symbols represent back-transformed mean and error bars represent 95% confidence limits on the means (n=4).

FIG. S3

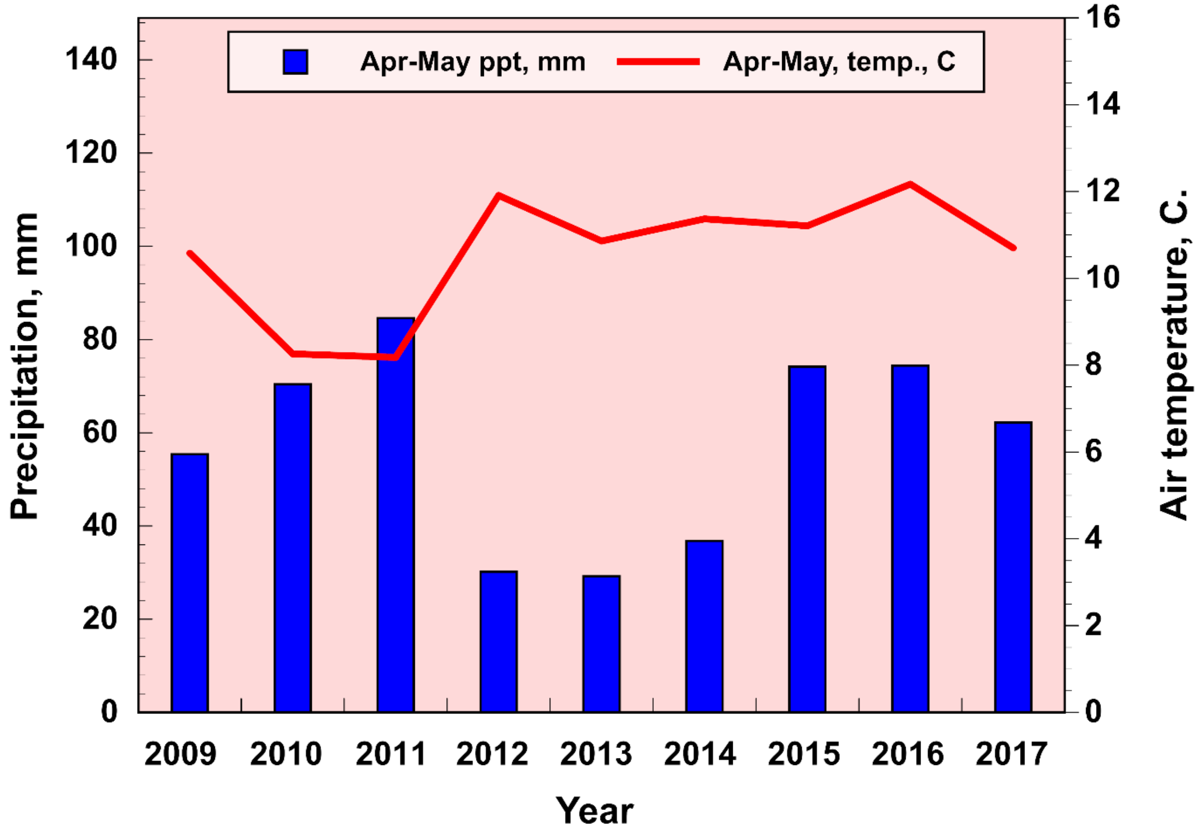

Fig. S3. Cumulative precipitation amounts and mean air temperature during Spring (April-May) in each year of the study.