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Changes in groundwater quality and agriculture in forty years on the Twin Falls irrigation tract in southern Idaho

R.D. Lentz, D.L. Carter, and S.V. Haye

Abstract: Understanding long-term impacts of agricultural landscapes on shallow groundwater quality is needed to improve soil and water management in the Twin Falls irrigation tract in southern Idaho. In 1999 and 2002 through 2007, we resampled 10 of the 15 tunnel drains monitored in a late-1960s study to determine how nutrient concentrations and flow rates of outflows have changed over time in response to changes in land management or climate. Since the late 1960s, an 8-fold increase in the dairy herd has driven shifts toward increased feed cropping, which, along with improved hybrids and production, increased inorganic and manure fertilizer use. The late-1960s to early-2000s period saw a consistent 1.4-fold increase in mean tunnel-drain outflow nitrate-nitrogen (NO_3-N) concentrations (from 3.06 to 5.06 mg L^{-1} [ppm]), a 10% decrease in mean chloride (Cl) (from 49.2 to 44.2 mg L^{-1} [ppm]), and an overall 14% decrease in dissolved reactive phosphorus (DRP) (14 to 12 µg L^{-1} [ppb]). However, 3 of the 10 tunnels exhibited increased DRP concentrations during the period, and the rate of DRP increase was positively related to increasing encroachment of confined animal feeding operations or residential development. Decreases in tunnel flow between sampling periods were linearly related to corresponding increases in the fraction of sprinkler irrigation employed on lands drained by the tunnels ($p = 0.01$). However, further conversion from furrow to sprinkler irrigation is unlikely to reduce tunnel drain NO_3-N concentrations since the latter were unrelated to changes in sprinkler coverage. The amount and timing of applied N and availability for crop uptake or leaching should be more carefully managed in these soils to prevent continued increases in groundwater NO_3-N concentrations. It is recommended that alfalfa (*Medicago sativa* L.) rotations be followed by deep-rooted crops with large N requirements to better utilize N mineralized from killed alfalfa roots.

Key words: drainage—furrow irrigation—nutrient losses—sprinkler irrigation

Concerns about the quality of US water resources arose in the 1960s, resulting in passage of the Water Quality Act of 1965 (Public Law 89-234) and increased research on agriculture's impact on groundwater quality, with particular interest in irrigated agriculture of the western United States (Bower and Wilcox 1969; Meek et al. 1969). Optimal light and temperature conditions in the West, along with heavy nitrogen (N) and phosphorus (P) fertilizer applications, produced near maximum yields for irrigated crops. However, if soluble nitrates (NO_3) from N fertilizer leach below the root zone, they could contaminate groundwater (Johnston et al. 1965). To better understand irrigated agriculture's influence on surface and groundwater quality, Carter et al. (1970) sampled ground and surface waters from 1968 through 1970 in the 82,030 ha (202,702 ac) Twin Falls Canal Company (TFCC) irrigation tract, located in Twin Falls County, southern Idaho. Carter et al. (1973) collected subsurface drainage water from fifteen tunnel drain outlets and five tile-relief well network outlets in the subject area from 1968 to 1970. Compared to the irrigation water applied to the irrigation-tract soils, Carter et al. (1971) reported that subsurface drainage water contained greater NO_3-N concentrations (3.24 versus 0.12 mg L^{-1} [ppm]) on average and smaller dissolved reactive P (DRP; 12 versus 66 µg L^{-1} [ppb]) concentrations.

Agriculture in the TFCC tract has undergone changes in the several decades since the Carter et al. (1971) study that may have altered the area's subsurface water quality. Evaluating subsurface groundwater quality conditions since that study should help us understand how changes in agricultural management have influenced groundwater nutrients in the subject area. In Twin Falls County, various Idaho State agencies evaluated groundwater quality in domestic wells between 1991 and 1998 (Neely and Crockett 1999) and in dairy wells during 1999 to 2000 and 2001 to 2003 (Bahr and Carlson 2000; Tesch and Carlson 2004). However, these data cannot be compared directly to those of Carter et al. (1971) because the state's research sampled different water sources and used different sampling frequencies. Therefore, the objective of the current research was to (1) revisit and resample (in 1999 and in 2002 through 2007) some of the original subsurface drains Carter et al. (1970) monitored in 1968 to 1970; (2) assess current and past methods used to analyze water NO_3-N concentrations in these tunnel waters; and (3) compare nutrient status in outflows between the two periods in relation to changes in the area's agriculture. A companion paper reports on the ^{15}N and oxygen-18 (^{18}O) isotopic signature of NO_3 in the sample outflow from these same subsurface drains.

Materials and Methods

Twin Falls Canal Company Irrigation Tract. The TFCC irrigation tract is located in the upper Snake River basin of southern Idaho (figure 1) at an elevation of 884 to 1,250 m (2,900 to 4,100 ft). Shortly after the tract was developed, horizontal tunnel drains or relief well and tile drain networks were constructed to eliminate localized high water tables that formed as a result of irrigation (Carter et al. 1970). The tract was described in detail by Carter et al. (1970, 1971).

Study Area. The study area (figure 1), which includes the tunnel and tile network

Rodrick D. Lentz (corresponding author) is a research soil scientist and **David L. Carter** (retired) was a supervisory soil scientist for the USDA Agricultural Research Service (ARS), Northwest Irrigation and Soils Research Laboratory, Kimberly, Idaho. **Stanley V. Haye** is a soil conservation technician for the USDA Natural Resource Conservation Service (NRCS), Marsing, Idaho.

outlet drains monitored in 1968 to 1970 by Carter et al. (1971), is bounded in the south by the Lowline canal (42°30´30˝ N); in the north by the Snake River canyon (42°38´30˝ N); to the east by the town of Kimberly, Idaho (114°22´00˝ W); and to the west by Salmon Falls Creek (114°52´30˝ W). The climate is semiarid with mean annual precipitation of 254 mm (10 in) and mean annual temperature of 9.5°C (49.1°F). The soils are well drained, dominated by silt loam textures, and typically include silica and calcium carbonate ($CaCO_3$) cemented horizons at 0.25 to 1 m (10 to 40 in) depths (USDA NRCS 1991).

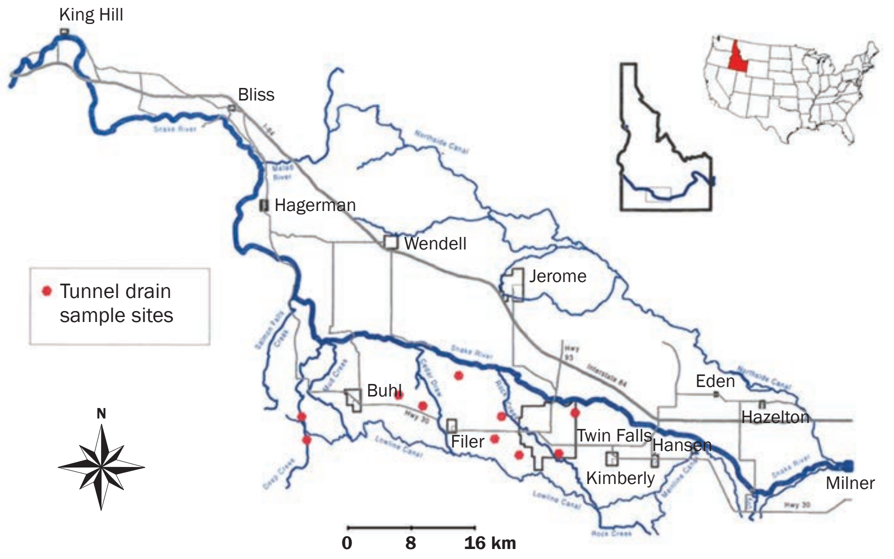
Crops require irrigation, which traditionally was surface applied in furrows, but a slow conversion to sprinkler irrigation began in the mid-1990s (Bjorneberg et al. 2008). The major crops grown in the area are alfalfa (*Medicago sativa* L.), small grains including barley (*Hordeum vulgare* L.), spring and winter wheat (*Triticum aestivum* L.), dry bean (*Phaseolus vulgaris* L.), sugarbeet (*Beta vulgaris* L.), potato (*Solanum tuberosum* L.), and corn (*Zea mays* L.) for grain or silage. Conventional tillage is a common practice in furrow irrigated fields, but conservation tillage practices are being increasingly employed under sprinkler irrigation.

Agricultural Management History. We compared agricultural practices currently used in Twin Falls County to those employed in 1968 to 1970 using two methods. Data obtained from the USDA National Agricultural Statistics Service (NASS) US Agricultural Census (USDA NASS 2016) provided snapshots of farming management used in Twin Falls County at four- or five-year intervals beginning in 1964 and continuing through 2012. In addition, a small sampling of long-time farmers in the TFCC tract were interviewed to obtain individual, first-hand accounts of changing farm practices.

Experimental Design. The experiment was organized as a randomized complete block, where sampling periods and months were included as treatment factors, and where individual tunnel drains comprised the replicates. From this point forward, the terms "YrGrp1" or "late-1960s" will refer to the sampling period from spring 1968 through fall 1970, and "YrGrp2" or "early-2000s" will refer to the sampling years 1999 and 2002 through 2007.

Figure 1

Study area within Twin Falls Canal Company irrigation tract in south-central Idaho.



Sampling and Analysis. In the 1968 to 1970 study, Carter et al. (1971) sampled outlet water one to two times a month from 15 tunnel and tile-well network drains across the TFCC tract. In the current study, we revisited and randomly sampled 10 of the original drains, which were stratified by area to ensure complete coverage of the study lands. In both studies, water samples were also collected at the Milner Dam pool, which supplies water to the irrigation canals. Similar to the 1968 to 1970 study, water samples were collected once per month during the April to November irrigation season and on alternate months in the off-season in 1999 and 2002 through 2007. We collected water samples from the flow issuing directly from the tunnel or tile drain outlet and stored them on ice until transported to the lab. The water from drains contained no sediment. Carter et al. (1971) analyzed samples within 48 hours, whereas the current study stabilized samples with boric acid (Lentz 2013) and refrigerated at 4°C (39°F) until analyzed. Lentz (2013) showed that this procedure produced stable NO_3-N and DRP values for sediment-free water samples stored for over three months. An automatic, colorimetric flow injection analyzer (Lachat Instruments, Loveland, Colorado) determined NO_3-N using cadmium (Cd) reduction of NO_3 to nitrite (NO_2) (Quik Chem Method 10-107-04-1A), and chloride (Cl) using the ferricyanide method (Quik Chem Methods 10-117-07-1-B). The DRP in the samples was determined by the ascorbic acid method (Kuo 1996). The minimum detection limit for NO_3-N and DRP was 10 µg L^{-1} and minimum detection for Cl was 0.8 mg L^{-1}.

Carter et al. (1971) used the phenoldisulfonic acid (PDSA) method (US Salinity Laboratory Staff 1954) to determine NO_3 values for their 1968 to 1970 study. We employed the flow injection analysis (FIA), PDSA, and chromotopic methods (American Public Health Association 1971) to measure NO_3-N concentration in split tunnel water sample volumes collected from the 10 tunnel drains on three occasions in March of 1993. Results from the 30 samples showed that PDSA consistently and significantly underestimated FIA. The PDSA values averaged 81% (standard deviation [SD] = 4%) of corresponding FIA and the 95% confidence limit for the correction factor was 0.81 ± 0.02 (table 1). The outcomes of the statistical analyses did not change meaningfully when the NO_3-N concentration correction factor was varied within the range of its confidence limits. Therefore we adjusted the late-1960s tunnel drain NO_3-N concentration values to FIA equivalents (FIA equals PDSA divided by 0.81), and these were used in all calculations and statistical analyses and reported in tables and figures. Carter et al.'s (1971) methods for measuring DRP and Cl in water samples were either the same as (DRP), or comparable to (Cl, Mohr's method) (Sheen et al. 1938; Fishman and Friedman 1989), those of the current study.

Tunnel Flow Rates. We obtained flow rates for only 6 of the 10 sampled tun-

Table 1

Three methods for determining nitrate-nitrogen (NO_3-N) concentrations (mg L^{-1}) in triplicate tunnel drain water samples are compared, and the mean fractional ratios relative to the flow injection analysis (FIA) method were computed, along with standard deviations and 95% confidence limits. Three sets of samples were collected at three different times in March of 1993 and analyzed using the three approaches.

	NO_3-N concentration and mean for each sampling date								
	PDSA			CTA			FIA		
Tunnel drain	March 24	March 24	March 29	March 24	March 24	March 29	March 24	March 24	March 29
Cox	4.0	3.9	4.0	4.6	4.5	4.5	4.81	4.83	4.83
CSI fish hatchery	2.5	2.6	2.6	3.1	3.2	3.4	3.23	3.24	3.30
Grossman	2.8	2.6	2.8	3.3	3.1	3.5	3.48	3.49	3.55
Nye	3.0	2.8	2.6	3.3	3.4	3.5	3.54	3.55	3.57
Tolbert	3.5	3.5	3.6	4.0	4.0	4.2	4.25	4.27	4.30
Walters	3.5	3.5	3.5	4.1	3.9	3.7	4.18	4.19	4.19
Herman	4.5	4.5	4.1	5.2	5.4	5.1	5.48	5.50	5.49
Harvey	3.5	3.5	3.5	4.0	4.1	3.8	4.25	4.26	4.27
Peavy	3.8	3.9	3.8	4.4	4.4	4.2	4.56	4.60	4.57
Hankins	3.5	3.0	3.8	4.5	4.2	4.3	4.60	4.48	4.51
Mean (std. dev.) n = 30	3.42 (0.57)			4.03 (0.61)			4.25 (0.65)		
PDSA/FIA or CTA/FIA ratio, mean (std. dev.) n = 30	0.81 (0.04)			0.95 (0.03)			—		
PDSA/FIA or CTA/FIA ratio 95% confidence limits (n = 30)	0.81 ± 0.015			0.95 ± 0.013			—		

Notes: PDSA = phenoldisulfonic acid. CTA = chromotropic acid. FIA = flow injection analysis.

nel drains from the Idaho Department of Environmental Quality or the TFCC. The flows were measured monthly using weirs for a minimum of five years between 1999 and 2014. During 1968 to 1970, Carter et al. (1973) measured flows monthly by weir, and obtained data for two or three years out of the three.

Calculations and Statistical Analysis. Mean water nutrient concentrations (10 sites) and mean drain flows (6 sites) were computed for each tunnel drain and month by averaging across years. The 12 mean monthly NO_3-N, DRP, and Cl concentration and flow values were averaged to compute annual means for each tunnel drain. We tested for YrGrp effects on annual mean tunnel concentrations and flow rates using analysis of variance (PROC Mixed [SAS 2012]). The model included YrGrp as the fixed effect with tunnel drain as the random effect. The DRP concentration values were transformed to stabilize variances and improve normality, and the means were back transformed to original units for reporting.

Month and YrGrp effects on NO_3-N, DRP, and Cl concentration and flow values were tested using PROC Mixed (SAS 2012), where YrGrp, month, and their interaction comprised the fixed effect, and tunnel drain and tunnel-drain multiplied by YrGrp comprised the random effect. The model included a repeated statement on month, where type equaled autoregressive moving average (ARMA) and subject equaled tunnel-drain multiplied by YrGrp.

Monthly mean nutrient losses (six sites) were calculated for each tunnel drain and year as the product of measured monthly flow rate and mean monthly nutrient concentration. Missing monthly nutrient concentration records in the 1999 and 2002 to 2007 data (typically, gaps were less than two months long) were estimated by linearly interpreting between the bracketing known values. Nutrient loss responses were transformed when needed and analyzed identically to that of concentration.

The SAS program PROC Reg (SAS 2012) was employed to test the hypothesis that changing flows between sampling periods are linearly related to corresponding changes in sprinkler irrigation use on lands served by tunnel drains. We calculated the fractional change in tunnel flow between the two sampling periods (flow ratio) as the ratio of early-2000s mean flow divided by late-1960s mean flow. The increase of sprinkler irrigation on land served by tunnel drains (Sprinkler fraction) was calculated in equation 1 as follows:

$$\text{Sprinkler fraction} = \text{Sfraction}_{2000} - \text{Sfraction}_{1960}, \qquad (1)$$

where Sfraction_{2000} is the fraction of the total land served by a tunnel drain that was sprinkler-irrigated (including lawns) or fallow in the early 2000s, and Sfraction_{1960} is the fraction of the total land served by a tunnel drain that was sprinkler-irrigated (including lawns) or fallow in the late 1960s. (Lawns and fallow areas were included because, like sprinkler irrigation, they decrease leaching relative to furrow irrigated lands.)

The same procedure above was used to test for the effect of the flow ratio on mean nutrient concentration and monthly losses, with concentration or losses represented as ratios of early-2000s to late-1960s values. In addition, we calculated a proximity ratio using the distance from each tunnel drain to the nearest confined animal feeding operation (CAFO) or residential development. The term CAFO is used only in a general sense here to identify dairy or feedlot operations with greater than 20 animals. Historic aerial imagery was used to identify land use changes. The proximity ratio equals the early-2000s distance divided by the late-1960s distance and has a value ranging from near zero to one. A proximity value of one indicates no change, and decreasing ratios indicate closer and closer encroachment of these land uses to the tunnel drained land during the period. Regression analyses evaluated the relationship between the proximity ratio and tunnel drain nutrient concentrations for those tunnels with proximity ratios less than one.

Results and Discussion

Climatic conditions changed between the late 1960s and early 2000s. At the Kimberly USDA Agricultural Research Service (ARS) weather station, mean annual air temperature increased from 8.8°C to 9.4°C (47.8°F to 49°F), with increases coming entirely during spring, summer, and fall months. We assume that this environmental heating also increased soil temperatures between the late 1960s and early 2000s. Soil temperature changes may potentially influence the fate of soil nutrients (see later discussion).

Agricultural Management History. Substantial changes in Twin Falls County agriculture occurred between the late 1960s and early 2000s. The order of crop importance (hectares grown) in 1969—dry bean = small grains = alfalfa > sugarbeet > corn silage/grain > potato—changed in 2007 to alfalfa > small grains > corn silage/grain > dry bean > sugarbeet > potato (figures 2a and 2b). Relative to the late 1960s, planted areas increased for alfalfa hay (1.25-fold), small grains (1.5-fold), corn for grain (2.1-fold), corn for silage (5.8-fold), and potatoes (1.5-fold), but decreased for dry bean (57%) and sugarbeet (42%). The increased productivity and plantings of crops such as hybrid corn and improved wheat cultivars having relatively high fertilizer requirements, and decreased plantings of bean, which requires relatively less fertilizer, coincided with a 2.2-fold increase in overall fertilizer applications to county farmland between the late 1960s (1969 and 1974) and early 2000s (1997 and 2002) (figure 2d). In the same period, N removed in harvested crops increased 1.7-fold on average (table 2). Note that the total P and potassium (K) removed in harvested crop also increased 1.7-fold on average during the period.

An important driver of these cropping changes was the 8-fold increase in the county's dairy herd size during the 1969 to 2007 period (figure 2b). Thus, the increase in applied soil nutrients with time was supplied from both organic and inorganic sources. The area of Twin Falls County farmland to which manure was applied grew from an estimated 1,700 ha (4,200 ac) in 1969 to 10,600 ha (26,200 ac) in 2007 (USDA NASS 2016), a 6.2-fold increase. That is the equivalent of 770 kg (1,690 lb) manure N applied annually to county soils in 1969 versus 6,370 kg (14,050 lb) in 2007. The mix of inorganic N fertilizers applied to agricultural land also changed between the late 1960s and early 2000s, following national trends. Nationally the ammonium sulfate (NH_4SO_4):urea fertilizer-use ratio declined from 1.5 in the late 1960s to 0.2 in the early 2000s (USDA ERS 2013). Use of N solution fertilizers has also increased during the period owing to their lower costs and multiple application options (USDA ARS 1961; USDA ERS 2013).

The 10 producers we interviewed included some families that began farming in the area before 1960. Results largely confirm data from USDA NASS statistics. All those interviewed included alfalfa, small grains, and (all but one) corn in their crop rotations. Potato, sugarbeet, and bean were the crops most commonly removed from rotations since the late 1960s; however, 50% of the interviewed producers still include bean, and 12% include sugarbeet and potato in their rotations. Three years of alfalfa are often incorporated into a grower's three-crop rotation, inserting it after one to three rotations (i.e., every three to nine years). Corn typically follows alfalfa in the rotation, but some producers may follow alfalfa with beans, wheat, or surgarbeet. Manure use has increased, particularly since the 1980s, with a small majority of those interviewed currently including it in their management, paying US$20 to US$40 per load, depending on distance to source and subsidies provided by the CAFO. One load is 18.1 Mg fresh weight or ~10 Mg dry weight (20 tn fresh weight or 11 tn dry weight). Five to ten truckloads of manure ha^{-1} (2 to 4 ac^{-1}) are commonly applied on wheat stubble in the fall or winter prior to a corn crop.

Commercial fertilizer applications steadily increased since the late 1960s to support increasing crop yield potentials, but price increases starting in 2008 motivated farmers to reduce rates and utilize manure where economically feasible. Manure amendments have allowed some farmers to eliminate commercial fertilizer applications on alfalfa and bean crops. On other crops, some have utilized split N applications through their sprinkler systems, are experimenting with variable-rate applications, or are exploring the use of cover crops to reduce fertilizer costs.

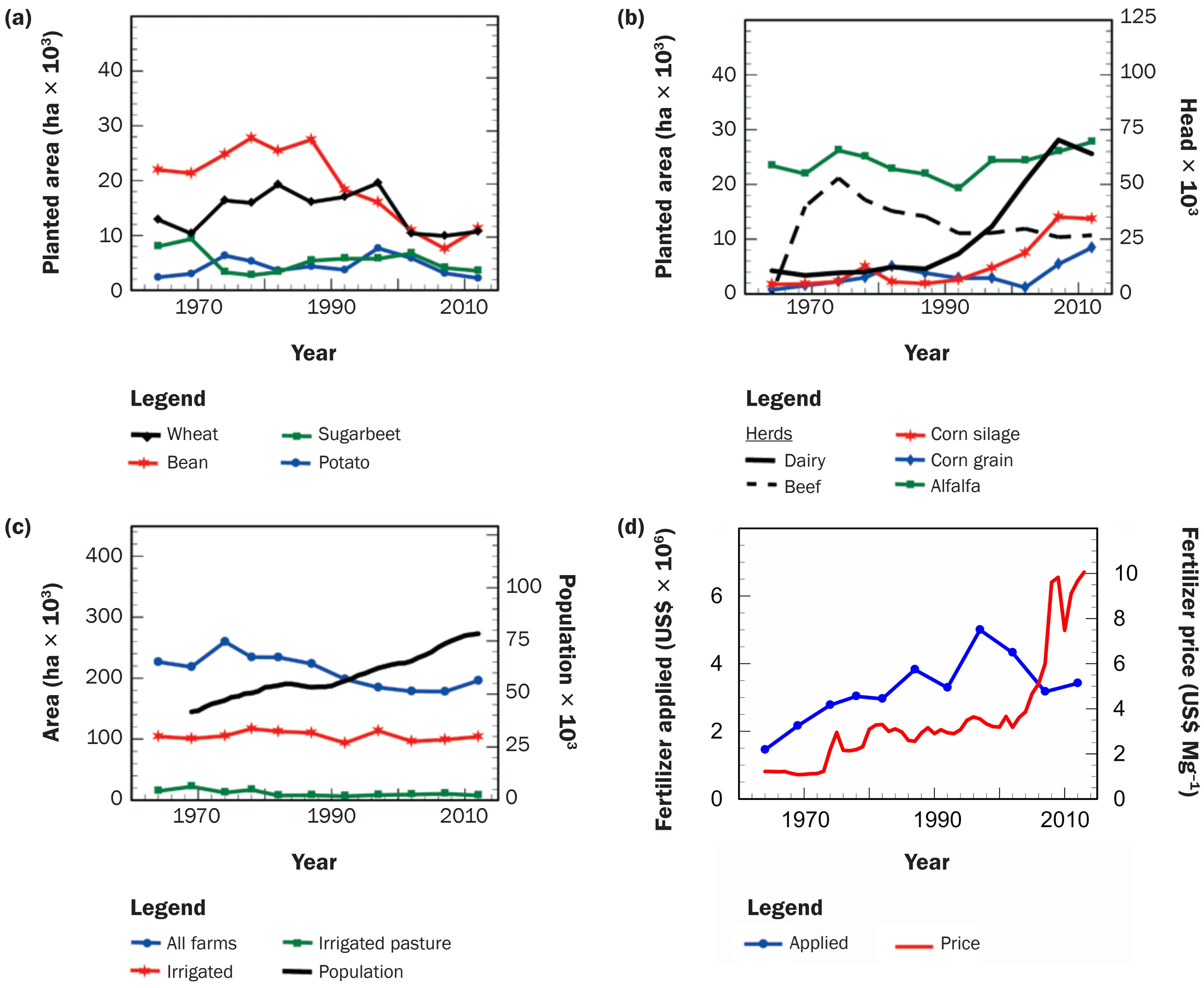
Tunnel Drain Nutrient Concentrations. The distribution of nutrient concentration values for tunnel drains are presented in figures 3a, 3b, and 3c, and for irrigation source water in figures 3d, 3e, and 3f. During the 40 years between the late 1960s and early 2000s, the annual mean NO_3-N concentration in tunnel drains increased 1.4-fold (from 3.60 to 5.06 mg L^{-1}), DRP decreased 14% (from 14 to 12 μg L^{-1}), and Cl decreased 10% (from 49.2 to 44.2 mg L^{-1}) (table 3). During the same period, mean NO_3-N concentration in the irrigation source water increased 1.3-fold (from 0.29 to 0.39 mg L^{-1}), and DRP decreased 23% (from 77 to 59 μg L^{-1}) (table 3). The tunnel drain increase in NO_3-N and decrease in Cl concentrations during the period is consistent across the tunnel drains (10/10 for NO_3-N and 9/10 for Cl), whereas DRP concentrations declined in seven tunnel drains, but increased in the other three (table 4).

When analyzed on a monthly basis, we observed a strong interaction between YrGrp and month on all nutrient concentrations in tunnel drain waters ($p < 0.0001$). Thus for each nutrient, the magnitude or seasonal pattern of tunnel drain concentrations differed between the two sample periods. Tunnel drain NO_3-N concentrations in the early 2000s are greater in each month than those of the late 1960s, but the seasonal patterns are similar with an annual peak occurring in winter months (figure 4a). Late-1960s tunnel drain DRP concentrations show a summer peak followed by a winter decline, where early-2000s values show little seasonal variation (figure 4b). Thus, recent seasonal DRP values are slightly greater in winter months, but less in summer months, than values observed in late 1960s. Like DRP, late-1960s tunnel Cl concentrations also display a summer peak followed by a winter decline, where the early-2000s pattern showed little variability (figure 4c). Hence, tunnel Cl concentrations for early summer through fall are slightly less than those seen in late 1960s. Irrigation source waters exhibited similar seasonal nutrient concentration patterns for both periods (i.e., NO_3-N and Cl values peak during the winter and decline in summer, while DRP values display two seasonal peaks, one in winter and one in late summer) (figure 4).

The NO_3-N concentrations in tunnel drain water samples are less than the US Environmental Protection Agency (USEPA)

Figure 2

Changes in Twin Falls County agricultural practices between 1966 and 2012, including: (a) hectares of wheat, bean, sugarbeet, and potato grown; (b) beef and dairy herd sizes relative to hectares of major animal feed crops grown; (c) area of county land dedicated to all farms, irrigated farms, and irrigated pasture, in comparison to Twin Falls County population; and (d) cost of fertilizer applied to county farms with average fertilizer price, both in 1968 to 1970 prices. Data from USDA National Agricultural Statistics Service (2016).



NO_3-N maximum contaminant level of 10 mg L^{-1} (Tesch and Carlson 2004) in all except a few cases during the early 2000s. The USEPA has no groundwater threshold concentration for total P, but the threshold for lake water is 50 μg L^{-1} (Sims et al. 1998). About 25% of the early-2000s tunnel drain water samples exceeded the 50 μg L^{-1} total P threshold, although annual mean values for individual tunnels, which ranged from 38 to 49 μg L^{-1} total P, did not exceed the USEPA total P threshold concentration for lake water.

Nutrient concentrations in irrigation water that percolates through the soil and mixes with groundwater are shifted relative to the source water, in our case irrigation source water. While the direction of these shifts for a given nutrient was consistent between YrGrps, their magnitude varied (figure 4). We assessed these shifts in concentration by examining mean annual values obtained by averaging the transformed monthly values (table 3). Relative to the source irrigation water within YrGrp, tunnel drain NO_3-N concentrations increased 12-fold in late 1960s, but increased 13-fold in early 2000s. The DRP concentrations in tunnel drains were reduced 82% relative to irrigation source water in the late 1960s versus an 80% reduction observed in the early 2000s. Finally, Cl concentrations in tunnel drains increased 2.2-fold relative to irrigation source water in late 1960s and 1.9-fold in the early 2000s.

Tunnel Drain Flow Rates. The analyses found no effect of YrGrp on either mean annual tunnel drain flow rates (p = 0.3) nor cumulative annual flows (p = 0.33), and the analysis of month-to-month values indicated a highly significant effect of month (p

Table 2

Yields and estimated total nitrogen (N) removed in harvested crops in Twin Falls County, Idaho, for selected periods, and changes between periods, given as the ratio of late to early times. Data from USDA National Agricultural Statistics Service (NASS) (2016).

	Mean yields*		Total N in harvested crop (Mg)*		Late to early period ratio	
	A (1969, 1974)	B (1997, 2002)	C (1969, 1974)	D (1997, 2002)	Yield (B/A)	N removed (C/D)
Total wheat (grain) (Mg ha^{-1})	45.60	72.66	1,766	3,149	1.52	1.78
Barley (Mg ha^{-1})	1.31	2.32	493	1,287	1.37	2.61
Dry edible bean (quintal ha^{-1})†	22.61	25.70	4.7	3.1	1.18	0.66
Potato (quintal ha^{-1})†	341.38	447.30	1.3	2.5	1.32	1.90
Sugarbeet (Mg ha^{-1})	20.21	25.90	1,216	1,537	1.22	1.26
Corn (grain) (Mg ha^{-1})	5.25	9.45	285	278	1.86	0.97
Corn (silage) (Mg ha^{-1})	42.34	54.99	449	1,447	1.36	3.00
Pea (quintal ha^{-1})†	21.22	24.81	—	—	1.11	—
Alfalfa hay (dry) (Mg ha^{-1})	9.81	12.04	7,315	10,548	1.21	1.44
Mean	—	—	—	—	1.40	1.70

*Yields are means from consecutive NASS census reports: A (1969, 1974); B (1997, 2002). Total N is calculated as the product of yield, area planted (figures 2a, 2b), and total N concentration of harvested tissue.

†quintal = 100 kg.

< 0.0001), but not YrGrp, nor YrGrp multiplied by month interaction on flows ($p > 0.32$). The mean annual tunnel drain flow rate averaged 0.218 ± 0.123 m^3 s^{-1} (7.70 ± 4.34 ft^3 sec^{-1}) in the late 1960s and 0.175 ± 0.079 m^3 s^{-1} (6.18 ± 2.79 ft^3 sec^{-1}) in the early 2000s. Differences in mean flow rates between the late 1960s and early 2000s varied by tunnel drain (table 4), and were related to changes in the type of irrigation (see later discussion on sprinkler fraction). Seasonal patterns for both the late-1960s and early-2000s tunnel flows exhibit a strong, sinusoidal form with an annual frequency, where flow rates decline to a minima in April (0.15 m^3 s^{-1} [5.3 ft^3 sec^{-1}] in 1960s versus 0.12 15 m^3 s^{-1} [4.24 ft^3 sec^{-1}] in 2000s), and rise to a maxima in September or October (0.29 m^3 s^{-1} [10.2 ft^3 sec^{-1}] in 1960s versus 0.23 m^3 s^{-1} [8.1 ft^3 sec^{-1}] in 2000s), in response to irrigation (table 5).

Tunnel Drain Nutrient Losses. From YrGrp 1 to 2, the mean monthly, cumulative NO_3-N losses from tunnel drains increased 1.2-fold, from 1.83 to 2.17 Mg mo^{-1} (2 to 2.4 tn mo^{-1}; $p = 0.02$), DRP decreased 22% from 7.19 to 5.62 kg mo^{-1} (15.8 to 12.4 lb mo^{-1}; $p = 0.001$), and Cl decreased 26% from 27.7 to 20.6 Mg mo^{-1} (30.5 to 22.7 tn mo^{-1}; $p = 0.0001$; table 3). When analyzed on a monthly basis, we observed a strong interaction between YrGrp and month factors for NO_3-N and DRP ($p = 0.001$), and a marginally significant interaction for Cl losses ($p = 0.07$). Compared to the late 1960s, the early-2000s NO_3-N losses were greater during the months of late-fall (figure 5a), coinciding with increased flow disparity between the two periods (table 5), and late winter, coinciding with increased difference in NO_3-N concentration between the two periods (figure 4a). Monthly DRP losses in the early 2000s are nearly half those of the late 1960s during June through September, but 1.5-to-2-times greater than late-1960s values during winter. Less Cl was lost in tunnel drain flows during the early 2000s than late 1960s, regardless of month, and like DRP, the difference between periods was greatest during summer and fall. The seasonal nutrient losses also follow a sinusoidal pattern, similar to that of flow rate.

Effect of Sprinkler Irrigation and Proximity Ratio. The regression analysis showed that decreases in tunnel flow between sampling periods were linearly related to corresponding increases in the fraction of sprinkler irrigation employed on lands drained by the tunnels ($p = 0.01$). The resulting fitted model is shown by equation 2:

$$\mathit{Flow\ ratio} = (-2.53 \times \mathit{Sprinkler\ fraction}) + 1.49, \tag{2}$$

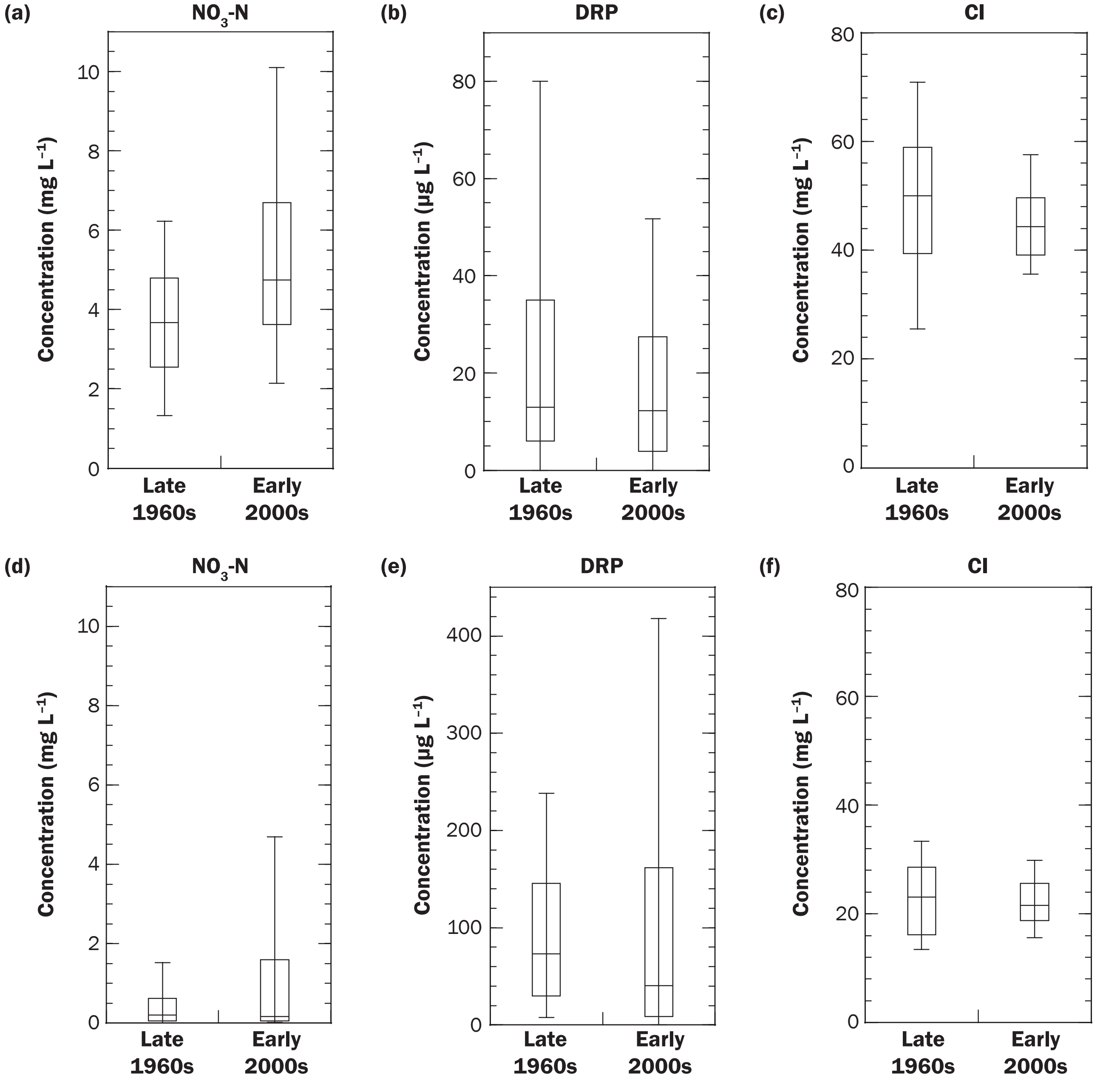
where *Flow ratio* is the fractional change in tunnel flow between the two sampling periods (early-2000s/late-1960s) and *Sprinkler fraction* is the increase of sprinkler irrigation on land served by tunnel drains between the two periods, $\text{Sfraction}_{2000} - \text{Sfraction}_{1960}$ (detailed definitions in the Calculations and Statistics section). The relationship produced an r^2 of 0.84. Thus, compared to late-1960s flows, early-2000s tunnel flows decreased as more of the land drained by the tunnels was sprinkler-irrigated.

Regression analysis further showed that individual tunnel drain NO_3-N, DRP, and Cl concentrations given as early-2000s:late-1960s ratios were not linearly related ($p = 0.26$ to 0.88) to the tunnel flow ratio during the period. By contrast, individual tunnel-drain NO_3-N, DRP, and Cl mass losses, also given as early-2000s:late-1960s ratios, are linearly and positively related to the tunnel-drain flow ratio ($p = 0.0001$ to 0.002) as expected since mass loss is computed as the product of flow rate and nutrient concentration. This implies that changes in tunnel-drain nutrient concentrations were not caused by the introduction of sprinkler irrigation, which decreased flow rates on lands served by drains.

The proximity ratio equaled unity for 6 of the 10 tunnel drains, indicating no encroachment of CAFO or residential development, but ranged from 0.03 to 0.86 for the remaining four tunnels (table 6). Notably, the three tunnel drains with the smallest proximity ratio (closer encroachment) were the same ones that experienced an increase in DRP concentrations during the period (tables 4 and 6). Regression of the proximity ratio on early-2000s:late-1960s concentration ratios indicated a significant relationship between proximity ratio and tunnel drain DRP concentrations ($p = 0.05$), but none with NO_3-N ($p =$

Figure 3

Stem and whisker plots showing (a and d) nitrate-nitrogen (NO_3-N), (b and e) dissolved reactive phosphorus (DRP), and (c and f) chloride (Cl) concentrations in (a, b, and c) tunnel drains or (d, e, and f) irrigation water for two measurement periods: late 1960s (1968 to 1970) and early 2000s (1999 and 2002 through 2007). Percentiles shown represent minimum and maximum values and 25%, 50%, and 75% percentiles. Note the different *y*-axis scales used for DRP between water types.



0.14) or Cl ($p = 0.16$). When both the proximity and DRP concentration ratio values were log-transformed, the proximity ratio was linearly related to the DRP concentration ratio. This indicates that as CAFO or residential development encroached more closely on tunnel drains, the increase in tunnel-drain DRP concentrations during the period became increasingly greater.

Agricultural Impacts on Groundwater Quality. We assume that water from wells located in rangelands and from deeper wells in the surrounding upper Snake River basin is representative of the Twin Falls regional groundwater, which is less sensitive to anthropomorphic influences compared to local groundwater (Fetter 1980). The regional groundwater NO_3-N concentrations range between 0.2 and 1.5 mg L^{-1} (Rupert 1994; Parliman 1988); therefore, tunnel drain water with NO_3 concentrations >2 mg L^{-1} are considered to be altered by human activity (Parliman 1988).

Table 3
Mean annual nutrient concentrations and mean monthly losses for tunnel drains and irrigation source water.

		Concentration*			**Losses*†**		
Tunnel name	**YrGrp**	**NO_3-N (mg L^{-1})‡**	**DRP (µg L^{-1})**	**Cl (mg L^{-1})**	**NO_3-N (Mg mo^{-1})‡**	**DRP (kg mo^{-1})**	**Cl (Mg mo^{-1})**
Tunnel drains	1	3.60b§	14a	49.2a	1.83a	7.19a	27.7a
	2	5.06a	12b	44.2b	2.17b	5.62b	20.6b
Irrigation source water	1	0.29a	77a	22.8a	—	—	—
	2	0.39a	59b	23.6a	—	—	—

Notes: YrGrp1 = spring 1968 through fall 1970. YrGrp2 = 1999 and 2002 through 2007. NO_3-N = nitrate-nitrogen. DRP = dissolved reactive phosphorus. Cl = chloride.

*Computed for each tunnel drain as the average of transformed monthly mean values, which were back-transformed, where needed, to original units (NO_3-N and Cl concentration and Cl loss data not transformed); value is the mean of 10 tunnel drains.

†Values are means of the six tunnel drains for which flow measurements were available.

‡The NO_3-N concentrations and mass losses for late-1960s samples were determined after adjusting concentration values to flow injection analysis (FIA) equivalents using FIA = PDSA ÷ 0.81.

§Within a water type, means in the same column followed by the same letter are not significantly different ($p < 0.05$)

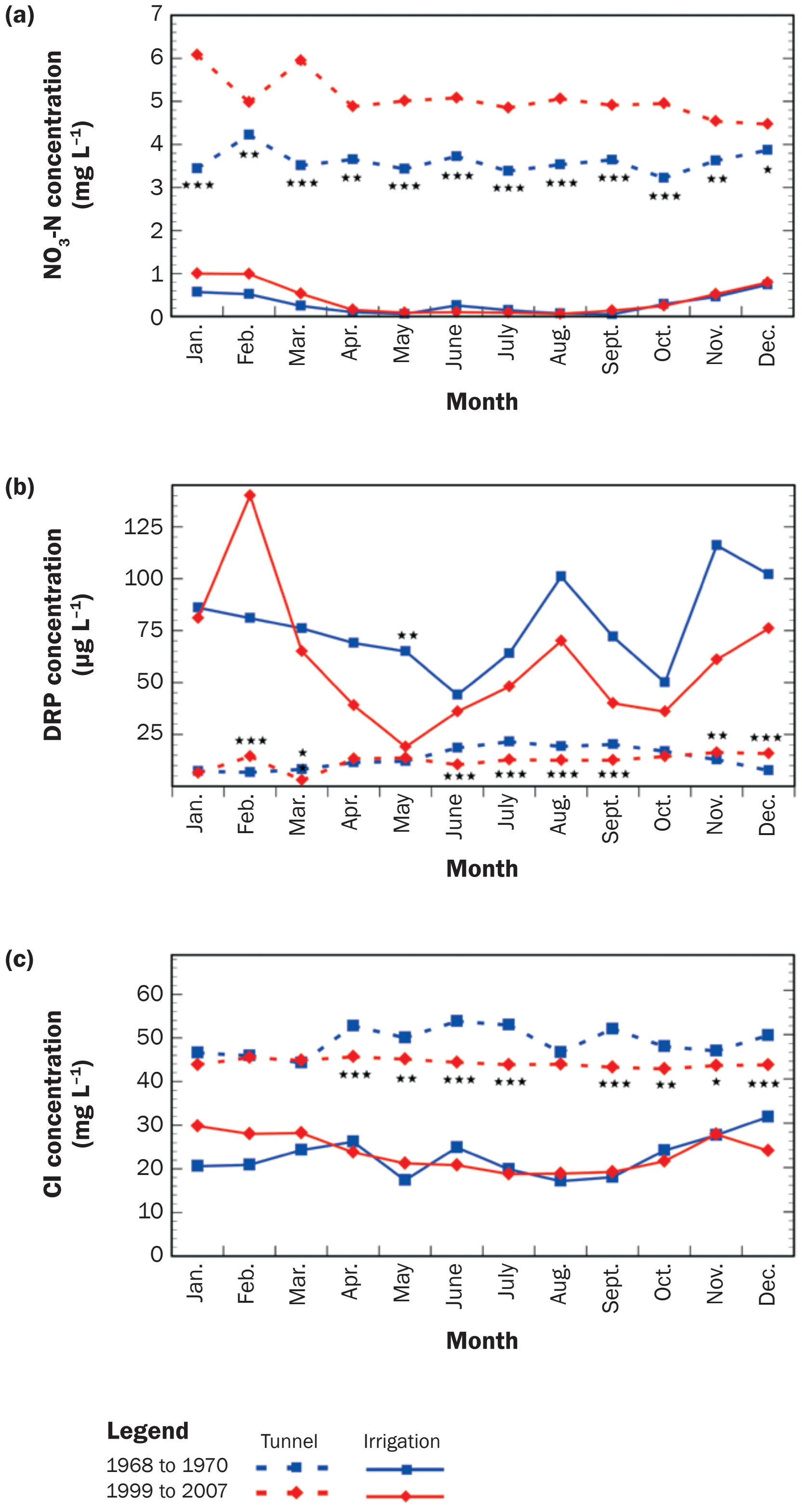
Table 4
Average flow, nutrient concentrations, and losses for each tunnel drain (TID) in the late 1960s (YrGrp = 1) and early 2000s (YrGrp = 2). Data is nontransformed.

				Concentration			**Losses**		
Tunnel name	**TID***	**YrGrp**	**Mean flow rate (m^3 s^{-1})**	**NO_3-N (mg L^{-1})***	**DRP (µg L^{-1})**	**Cl (mg L^{-1})**	**NO_3-N (Mg mo^{-1})***	**DRP (kg mo^{-1})**	**Cl (Mg mo^{-1})**
Cox	1	1	0.144	3.97	15.0	42.42	1.504	5.894	16.106
		2	0.209	5.97	14.5	40.57	3.275	8.095	22.331
CSI fish hatchery	2	1	0.171	2.68	13.9	43.62	1.193	7.102	19.110
		2	0.084	3.54	16.1	41.40	0.733	3.910	8.871
Grossman	3	1	—	2.91	15.1	40.65	—	—	—
		2	—	4.03	13.8	38.69	—	—	—
Hankins	4	1	—	4.26	11.9	55.61	—	—	—
		2	—	5.18	7.6	44.63	—	—	—
Harvey	5	1	0.431	4.05	18.9	46.22	4.593	21.717	52.561
		2	0.250	5.16	18.4	40.30	3.360	12.346	26.488
Herman (Dolan)	6	1	0.194	3.64	16.0	49.04	1.816	8.677	24.762
		2	0.103	6.72	17.0	46.63	1.825	4.961	12.628
Nye tile	7	1	—	2.92	10.2	52.66	—	—	—
		2	—	4.58	7.2	43.34	—	—	—
Peavy	8	1	0.108	3.65	9.7	53.20	1.032	2.757	15.098
		2	0.177	5.52	10.0	54.00	2.567	4.668	25.050
Tolbert	9	1	0.260	3.99	11.4	56.24	2.724	8.156	38.486
		2	0.223	5.16	7.5	47.64	3.021	4.435	27.934
Walters tile	10	1	—	3.94	13.6	52.48	—	—	—
		2	—	4.80	9.2	45.07	—	—	—

Notes: CSI = College of Southern Idaho. NO_3-N = nitrate-nitrogen. DRP = dissolved reactive phosphorus. Cl = chloride.

*The NO_3-N concentrations and mass losses for late-1960s samples were determined after adjusting concentration values to flow injection analysis (FIA) equivalents (i.e., FIA = PDSA ÷ 0.81).

Figure 4
Mean monthly (a) nitrate-nitrogen (NO_3-N), (b) dissolved reactive phosphorus (DRP), and (c) chloride (Cl) concentrations in tunnel drains or irrigation-source waters from late-1960s and early-2000s sampling periods. Symbols adjacent to monthly values indicate the significance of sampling period differences at given probability levels (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$).



The tunnel drain NO_3-N concentrations exceeded the natural background levels by at least 2.4-fold by the late 1960s (1.5 versus 3.60 mg L^{-1}; table 3), and 3.4-fold by the early 2000s. This increase is attributed primarily to the dominant impact of agriculture on lands drained by the tunnels. However, our data cannot rule out possible NO_3-N contributions from septic systems. Sprinkler irrigation has increased on these farmlands, but the evidence suggests that this had little influence on the nutrient concentrations (see section entitled Effect of Sprinkler Irrigation and Proximity Ratio). Recall that, while fertilizer applications to county farmland between the late 1960s and early 2000s increased 2.2-fold (figure 2d), overall N removal in harvested crops increased only 1.7-fold (table 2). Since irrigated farmland remained constant during the period (figure 2c), this suggests that fertilizer nutrient application to crops substantially increased above that needed to sustain production increases. Between 1997 to 2002 and 2007 to 2012, average fertilizer applications fell 32% in Twin Falls County to levels not seen since 1982 (figure 2d), yet average yields increased during that same period (table 1), further indicating that fertilizer was being applied excessively prior to 2007. Fertilizer use during the period exceeded crop production needs, which may have resulted in luxury consumption of N by crops, with surplus quantities of the nutrient leaching into the groundwater system.

Another factor contributing to increased tunnel-drain NO_3-N concentrations with time may be related to increased alfalfa plantings (figure 2b). Although the 1.25-fold increase in alfalfa planting during the period was the least for all the gaining crops, par-ticularly compared to the 5.8-fold increase for silage corn, the expanded alfalfa coverage likely increased NO_3-N leaching. Robbins and Carter (1980) reported that excess NO_3-N from mineralized roots of killed alfalfa are under-utilized by the subsequent crop, particularly a bean crop, and is leached from the root zone. Meek et al. (1995) found that both crop sequence and tillage influence NO_3-N leaching in years following an alfalfa crop in these soils. The nonsignificant rela-tionship observed between the individual tunnel drain NO_3-N concentrations, given as early-2000s:late-1960s ratios, and proximity ratio indicates that encroaching CAFO or residential development were not the primary drivers for the increase in tunnel drain

Table 5

Mean monthly tunnel-drain flow rates ($m^3\ s^{-1}$; with standard deviations in parentheses) for the two measurement periods (YrGrps). Values are means of the 6 out of 10 tunnel drains for which flow measurements were available.

Period	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1968 to 1970	0.20	0.20	0.16	0.15	0.17	0.20	0.21	0.26	0.29	0.29	0.26	0.23
	(0.11)	(0.11)	(0.09)	(0.09)	(0.09)	(0.10)	(0.10)	(0.12)	(0.16)	(0.16)	(0.16)	(0.15)
1990 to 2007	0.17	0.15	0.13	0.12	0.12	0.14	0.17	0.21	0.23	0.23	0.23	0.19
	(0.07)	(0.06)	(0.06)	(0.07)	(0.07)	(0.06)	(0.07)	(0.08)	(0.08)	(0.08)	(0.09)	(0.08)

NO_3-N concentrations over time. This evidence suggests that that tunnel NO_3-N concentrations were more strongly influenced by increased inorganic fertilizer inputs or increased alfalfa plantings.

The DRP concentrations in tunnel waters were low, typical for shallow groundwater in agricultural lands of the western United States (Brookes et al. 1997; Domagalski and Johnson 2011). It is not clear why an overall 10% decrease in tunnel water DRP concentrations occurred between the late 1960s and early 2000s (table 3). In calcareous soils, DRP concentration in leachate water is largely controlled by P adsorption on soil particles and precipitation with calcium (Ca) (Johnson and Cole 1980; Leytem and Westermann 2003; Domagalski and Johnson 2011; Gbolo and Gerla 2015). Sorption of P in soil can increase with temperature (Holtan et al. 1988), and Ca-P precipitation decreases with increasing soil SO_4^{-2} concentration (Kumaragamage et al. 2004). Thus, the decline in tunnel water DRP concentrations between the late 1960s and early 2000s may be related to increased soil temperatures and decreased NH_4SO_4 fertilizer applications, which combine to increase P sorption and precipitation reactions in the soil.

The relationship between encroaching CAFO or residential development and increasing tunnel-drain DRP concentrations during the period for some drains suggests that manure applications or septic system effluent (or sanitary sewer leakage) are impacting shallow groundwater (Brookes et al. 1997; Sims et al. 1998; Landon et al. 2008; Domagalski and Johnson 2011). Measured DRP concentrations in leachate from these sources are as great as 600 μg L^{-1} in septic effluent (Whelan and Titamnis 1982), and 2,400 μg L^{-1} in leachate from cattle feces (Jensen et al. 2000). However, sorption and precipitation processes limit transport of DRP through medium textured, calcareous soils. Phosphorus transport may occur when (1) sorption sites are saturated under high soil P loads, as might occur in CAFO associated soils (Sims et al. 1998; Robinson 2015) and, particularly likely, when water flow through the soils is dominantly through macropores, whose limited surface area is more quickly saturated or occluded (Westermann et al. 1999); (2) an increased presence of inorganic and organic anions compete with soil DRP for adsorption sites (Kafkafi et al. 1988; Jensen et al. 2000); (3) fluctuations in the kind and abundance of soil nutrients or cations induce rapid DRP release into soil solution (Lentz 2006); and/or (4) waterlogged soils lead to anerobic conditions and release P through the reduction of iron(III) (Fe^{+3}) compounds (Leinweber et al. 2002).

If the increase in DRP concentrations from these few tunnel drains is the result of increased P-loading and saturation of sorption sites along macropore pathways, an important question arises. Can these conditions be mitigated? Lentz and Westermann (2001) reported DRP concentrations in soil water leached below the 1.2 m (3.9 ft) soil depth in a Twin Falls County field that had received regular manure applications from 1969 to 1986. Even though no manure had been applied to the field in the previous 17 years, DRP concentrations in soil drainage water at 1.2 m depth averaged 1,100 μg L^{-1} at 50% of the locations sampled (Lentz and Westermann 2001). Gbolo and Gerla (2013) reported elevated DRP concentrations in shallow wells around a CAFO, which had been abandoned 12 years earlier. Schoumans and Groenendijk (2000) concluded that, in soils subject to intensive animal husbandry where P-leaching is problematic, several decades will be required to reduce water-soluble P levels to levels that meet environmental standards. This indicates that once these P-transport zones develop, they can have long-term, negative effects on drainage water quality (Sharpley et al. 2013).

Several US Geological Survey (USGS) groundwater studies in agricultural land, to the north of the Twin Falls Canal Tract but across the Snake River, and 100 km (60 mi) northeast of the study area, measured either NO_3, Cl, or DRP concentrations in well-water during 1988 to 1991 and again in 2001 to 2012 (Rupert 2008; Lindsey and Rupert 2012; USGS 2012). A quantitative comparison of nutrient concentration changes with time (between the current and USGS studies) is not valid owing to differences in hydrology, temporal sampling density, and depth of groundwater source sampled. In qualitative terms, USGS studies reported that well-water NO_3 increased, whereas DRP and Cl concentrations decreased over the decade, results that are identical to those of the current study (Rupert 2008; Lindsey and Rupert 2012; USGS 2012).

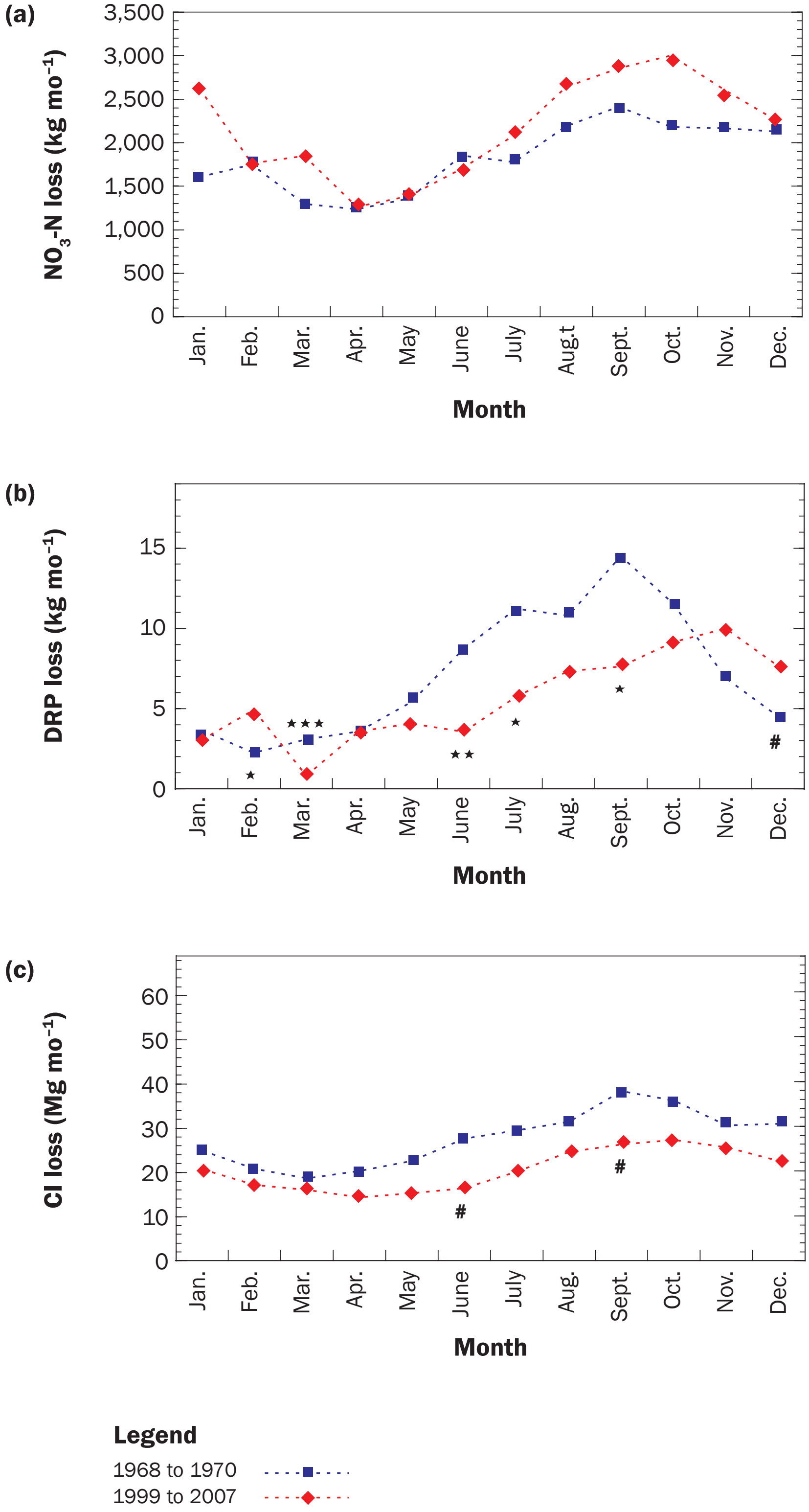
Summary and Conclusions

We conducted research to better understand how changing agricultural management in the Twin Falls Irrigation District during the period between the late 1960s and early 2000s has influenced shallow groundwater quality. An 8-fold increase in the dairy herd during the period prompted shifts toward increased feed cropping, which, along with improved hybrids and production, increased inorganic and manure fertilizer use. The following conclusions were made:

1. Tunnel drain NO_3-N concentrations have increased with time and late summer/fall NO_3-N losses have increased with time, indicating increased leaching of excessive NO_3-N derived from applied commercial and organic N fertilizers and mineralization of crop residues, with potential contributions from septic systems.
2. Evidence suggests that increasing the proportion of sprinkler irrigation relative to furrow irrigation will not reduce tunnel drain water NO_3-N concentrations.
3. In irrigated cropping systems, the amount and timing of applied N and availability for crop uptake or leaching need to be more carefully managed to prevent continued increases in shallow groundwater NO_3-N concentrations. In addition, crops planted in fields fol-

Figure 5

Mean monthly (a) nitrate-nitrogen (NO$_3$-N), (b) dissolved reactive phosphorus (DRP), and (c) chloride (Cl) losses in tunnel drain flows from late-1960s and early-2000s sampling periods. Values are means from 6 of the 10 monitored tunnel drains for which we obtained flow measurements. Symbols adjacent to monthly values indicate the significance of sampling period differences at given probability levels (# $p < 0.10$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$).



lowing alfalfa should be selected to efficiently utilize the abundant N mineralized from legume's root residue.

4. Tunnel drain DRP concentrations generally have not increased with time.
5. There is evidence, however, that high P-loading from manure or residential sewerage is saturating soil surfaces, lining water flow paths in some area soils, particularly those dominated by macropore flow, leading to increasing leaching of DRP. This is a concern because once developed, these conditions become long-term problems that are difficult to remediate.

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Table 6
Name, location, and elevation of tunnel drains (TID) monitored in the study, and irrigation used on land served by each drain in the late 1960s (YrGrp = 1) and early 2000s (YrGrp = 2).

Tunnel name	TID	Location*	Elev. (m)	YrGrp	Land use	Fractional coverage and irrigation used on land served by drain†	Proximity ratio‡
Cox	1	42E 34.05' N	1,106	1	C	Fr 1.0	0.86
		114E 50.12' W		2	C	Fr 1.0	
CSI fish hatchery	2	42E 32.67' N	1,117	1	C, P	Fr 1.0	0.03
		114E 27.84' W		2	H, P, F	Fr 0.55; R-F 0.45	
Grossman	3	42E 32.85' N	1,216	1	P	Fl 1.0	1.00
		114E 30.34' W		2	P	Fl 1.0	
Hankins tile	4	42E 35.10' N	1,110	1	C	Fr 0.85; S 0.15	1.00
		114E 25.28' W		2	P, F, R	Fr-Fl 0.48; S-F 0.52	
Harvey	5	42E 36.36' N	1,140	1	C	Fr 1.0	1.00
		114E 42.53' W		2	C	Fr 0.70; S 0.30	
Herman (Dolan)	6	42E 32.99' N	1,198	1	C, P	Fr-Fl 1.0	0.26
		114E 49.94' W		2	C, P	Fr-Fl 0.75; S 0.25	
Nye	7	42E 33.33' N	1,232	1	C	Fr 1.0	1.00
		114E 31.54' W		2	C	S 0.90; Fr 0.10	
Peavy	8	42E 35.06' N	1,176	1	P	Fl 1.0	0.15
		114E 39.14' W		2	P	Fl 1.0	
Tolbert	9	42E 34.62' N	1,031	1	C	Fr 1.0	1.00
		114E 31.28' W		2	C	Fr 0.68, S 0.32	
Walters tile	10	42E 37.74' N	1,032	1	C	Fr-Fl 1.0	1.00
		114E 35.705' W		2	C, P	Fr-Fl 1.0	

Notes: Elev. = elevation. C = cropped. F = fallow. Fl = flood irrigation. Fr = furrow irrigation. P = pasture. R = residential. S = sprinkler irrigation.

*Uses WGS84/NAD83 datum.

†The irrigation coverage fraction was computed as a mean value weighted by the number of years the irrigation was practiced during years of flow measurement. Furrow and flood were considered together, and sprinkler, residential lawns, and nonirrigated areas were considered together, when computing fractional coverage.

‡Proximity to dairy/feedlot or housing given as ratio (early-2000s/late-1960s).

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