

SURFACE WATER QUALITY IMPACTS FROM GOLF COURSE FERTILIZER AND PESTICIDE APPLICATIONS

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ABSTRACT

The impacts of fertilizer and pesticide applications on surface water quality were evaluated at a Pacific Northwest golf course over a two-year period. Fertilizer and pesticide application histories were compared to precipitation data to characterize nutrient and/or pesticide transport conditions. Monthly surface water samples were collected where a creek entered (entrance point) and exited (exit point) the golf course, and were analyzed for nitrate-N and orthophosphate. This analysis indicated that transport of nitrate-N and orthophosphate into surface water did not occur following fertilizer applications to the golf course. Matching samples were also analyzed for the presence of all pesticide active ingredients applied to the golf course since the last sample collection event (approximately one month). Of the total of 104 pesticide active ingredients applied during the study period, one active ingredient (triclopyr) was detected in the exit point sample at $0.1 \mu\text{g L}^{-1}$. The results of this study indicated that there were no significant impacts on surface water quality following the application of fertilizers or pesticides to the golf course.

Abbreviations: a.i. = active ingredient, K_{oc} = organic carbon partition coefficient, N = nitrogen, P = phosphorus.

Keywords: fungicide, herbicide, insecticide, nitrate, phosphate

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INTRODUCTION

Regulatory standards and public expectations increasingly demand protection of water quality from chemicals applied to golf courses. In addition to concerns about pesticides, attention has recently been directed toward the impacts of fertilizers (Minnesota Statutes, 2004). The regular use of pesticides and fertilizers on golf courses often leads to the assumption that these chemicals are transported into surface water and/or groundwater following application. This perception is often reinforced by information posted on the internet, public interest position publications (Primi et al., 1991), and technical reports. For example, a recent United States Geological Survey technical report identified 27 pesticide a.i.'s or pesticide degradation products in surface water samples collected from a watershed basin located near Portland, OR (Carpenter, 2004). Sixteen of the 27 compounds were listed as being used on golf courses, inferring that some of the detections may have resulted from golf course applications. However, eight of these 16 pesticides {atrazine [6-chloro-N²-ethyl-N⁴-isopropyl-1,3,5-triazine-2,4-diamine], dacthal [dimethyl tetrachloroterephthalate], *p,p'*-DDE [dichlorodiphenyltrichloroethane breakdown product], diazinon [O,O-diethyl O-(2-isopropyl-6-methyl-4-pyrimidinyl) phosphorothioate], fonofos [O-ethyl S-phenyl ethylphosphonodithioate], malathion [Diethyl (dimethoxythiophosphorylthio) succinate], metolachlor [2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl) acetamide], and simazine [6-chloro-N,N²-diethyl-1,3,5-triazine-2,4-diamine]} are not registered for use on Pacific Northwest golf courses and atrazine and simazine are highly injurious to grasses grown in the Pacific Northwest.

To prevent negative impacts on water quality from fertilizer and/or pesticide applications, contemporary golf course

management uses a combination of best management practices, integrated pest management strategies, improved chemical application methods and equipment, and the selection of products based on environmental fate. While this management approach is designed to protect water quality, its actual effectiveness is not well documented. Basic research ranging from predictive modeling studies (Haith and Rossi, 2003, Raturi et al., 2003) to highly controlled, small-scale studies (Kenna, 1995) has evaluated nutrient and pesticide transport from golf course turfgrass into surface water and/or groundwater, yet little research has been performed on this subject at the field-scale. Although monitoring fertilizer and pesticide impacts on water quality is often a condition of permits issued to golf courses, these field-scale data are generally not accessible to the scientific community (Cohen et al., 1999).

The objective of this study was to evaluate the impacts of fertilizer and pesticide applications on surface water quality on a field scale level at a Pacific Northwest golf course, paying special attention to precipitation events in relation to product application.

MATERIALS AND METHODS

Study Site

The study was performed at a private 18-hole golf course, Royal Oaks Country Club, located in an urban setting in Vancouver, Washington, USA. The course was constructed in 1945 using native materials, and the topography of the site was relatively uniform with mild slope and contouring. The predominant soil type (approximately 80%) was Lauren gravelly loam (medial-skeletal, mixed, mesic Pachic Melanoxerands), 0–8% slope. The soil on the northwest end of the site (approximately 15% of total) was Wind River gravelly loam (coarse-loamy, mixed, superactive, mesic

Ultic Haploxerolls), 0-8% slope. A small amount (approximately 5% of total) of McBee coarse variant silt loam (fine-silty, mixed, superactive, mesic Aquic Cumulic Haploxerolls) was located on the northeast and eastern boundaries of the golf course.

Three putting greens were rebuilt with sand-based rootzones in the mid 1970's, with the remainder consisting of native material that has been topdressed consistently with sand. Tees and fairways were all built from native soil. The golf course had approximately 25 hectares of maintained turfgrass including annual bluegrass (*Poa annua* L.) on putting greens, and a combination of *Poa annua* L. and perennial ryegrass (*Lolium perenne* L) for all remaining turfgrass areas. Course maintenance was representative of other country clubs in the region, and included a documented integrated pest management program.

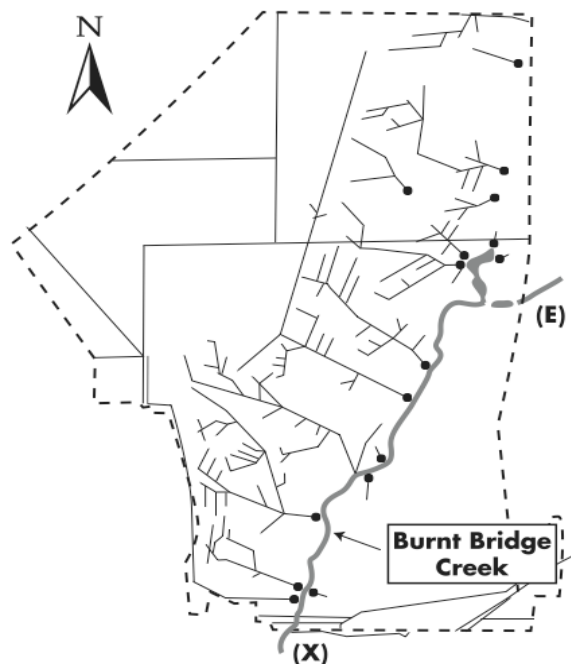


Figure 1. Map of study area including location of Burnt Bridge Creek, drain pipe network, and water quality monitoring sampling locations. Dashed line: golf course boundary. Closed circles: drain pipe outlets. (E) entrance point sampling location. (X) exit point sampling location.

Burnt Bridge Creek passed through a large portion of the golf course. The creek entered the eastern boundary of the golf course and proceeded in a southwesterly direction where it exited the golf course on its southern boundary (Fig. 1). Fairways and rough bordered both sides of the creek for approximately 80% of the length of its passage through the golf course, with fairways as close as 8 m to the water in some places. In addition, three greens were situated within 50 m of the creek. Two ponds were located on the golf course, with one directly connected to Burnt Bridge Creek, and the other not connected, serving as the irrigation pond. Shallow subsurface drainage pipes were located throughout a substantial area of the golf course, draining into Burnt Bridge Creek (Fig. 1).

Study Interval

The study was initiated on 3 Jun 2002 and concluded on 4 May 2004. Fertilizer and pesticide application histories and weather data were organized by year (year one, May 2002 – April 2003; year two, May 2003 – April 2004) to allow comparisons of yearly management conditions.

Fertilizer and Pesticide Applications

Complete fertilizer and pesticide inputs were provided monthly by the golf course superintendent. Fertilizer applications were reported by date, location (i.e., tees, fairways, greens, etc.) and N and P rate. Pesticide applications were also reported by date, location and rate.

Fertilizer Nitrogen.

Yearly N inputs are shown in Table 1. Nitrogen was applied to 11 individual areas (24.8 ha total), and the total amount applied during year one (3204 kg) was similar to the amount applied during year two (3183 kg). Slow release N represented 60% of the total N applied during year one and 45% during year

Table 1. Yearly nitrogen, phosphorus, and pesticide inputs by location.

Location†	N (kg)		P (kg P ₂ O ₅)		Fungicides (kg a.i.)		Herbicides (kg a.i.)		Insecticides (kg a.i.)	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
A	93	81	12	33	16	26	0	0	0	1
BR	475	223	33	27	0	0	1	3	0	18
BE	2	4	0	2	0	0	0	0	0	0
R	63	66	4	45	0	0	0	0	0	0
FBS	15	15	1	2	0	0	0	0	0	0
FW	1901	2003	222	309	63	32	0	0	68	67
G	252	161	37	121	125	118	0	0	5	4
GS	88	45	7	5	0	0	<1	0	6	20
T	238	324	78	181	75	55	<1	0	3	3
Tgt	18	20	5	11	5	3	<1	0	<1	<1
TS	59	59	8	7	0	0	<1	0	0	4
M	0	181	0	35	0	0	<1	<1	0	0
Total	3204	3183	407	777	284	235	2	3	83	117

†A= Approaches (0.5 ha), BR = Border Rough (6.1 ha), BE = Bunker Edges (0.1 ha), F = Fairways (12.2 ha), FBS = Bunker Surrounds (0.4 ha), G = Greens (1.3 ha), GS = Green Surrounds (1.2 ha), M = Miscellaneous (i.e., new sod, fairway walkways), R = Driving Range (0.8 ha), T = Tees (1.3 ha), Tgt = Target Greens (0.1 ha), TS = Tee Surrounds (0.8 ha).

two. Slow release N formulations included methylene urea, polymer coated urea, sulfur coated urea, and triazone. The average proportion of applied N was greatest for fairways (61%) followed by border rough (11%), tees (9%), greens (7%) and approaches (3%). The remaining N was applied in smaller amounts to other areas of the golf course. In general, the amount of N applied to specific areas was consistent for both years, although the border rough received more N during year one than year two. During year two, N was applied to miscellaneous areas (spot applications, new sod, fairway walkways) that did not receive N during year one.

For both years, four major N inputs equaled 87% of the yearly total. For year one, N inputs were lowest during Jan 2003 through Mar 2003 (2% yearly total), and for year two were lowest during Dec 2003 through Feb 2004 (3% yearly total).

Fertilizer Phosphorus.

Yearly P inputs are shown in Table 1. The average proportion of applied P was greatest for fairways (45%), followed by tees (22%), greens (13%), border rough

(5%), and approaches (4%). The remaining P was applied in smaller amounts to other areas of the golf course. The amount of P applied in a number of locations increased during year two in response to soil test results. In general, P applications coincided with N applications, although P was not applied during the winter months. The ratio of P to N was higher during spring applications for both years.

Pesticides.

Yearly inputs of fungicides, herbicides, and insecticides, and application locations are shown in Table 1. A total of 368 kg a.i. was applied during year one, and 356 kg a.i. were applied during year two.

Fungicides made up 77% of the active ingredients applied during year one, and 66% during year two. Target diseases and causal organisms included fusarium patch (*Microdochium nivale* [Fries] Samuels & I.C. Hallett), anthracnose (*Colletotrichum graminicola* sensu lato Crouch, Clarke, and Hillman [formerly *C. graminicola* (Ces.) G.W. Wils.]), pythium (*Pythium* spp.), brown patch (*Rhizoctonia*

solani Kuhn) and dollar spot (*Sclerotinia homeocarpa* F.T. Bennett). Fungicide applications were limited to five areas (approaches, greens, tees, target greens, and fairways). For both years, fungicide use during late spring and summer was comparatively low. Thirty eight percent of the total fungicide applied during year one occurred in Nov in response to a severe disease outbreak. Periodic fungicide applications continued through the winter and into the spring. For year two, 49% of the yearly fungicide applications occurred in Nov and Dec. Disease pressure subsided earlier in the spring of year two compared to year one.

Insecticides represented 22% of the active ingredients applied to the golf course during year one, and 33% during year two. Insecticide target areas included approaches, greens, tees, tee and green surrounds, fairways, border rough, and target greens. Insecticide use increased during year two due to an outbreak of bluegrass billbug (*Sphenophorus parvulus* Gyllenhal).

Herbicides were applied as spot-treatments only during both years, and represented less than 1% of total active ingredients applied each year.

Weather Data

Mean monthly temperature and precipitation data for the location (station Vancouver 4 NNE, Washington) were acquired from the Western Regional Climate Center (Reno, NV) database. Long term (116 year) means included the years 1891 – 2007. Daily precipitation data were acquired from the HYDRA network (Portland, OR) database for the Airport Way #2 rain gage station, located approximately 8 km south of the golf course.

Water Quality Monitoring - Sample Collection and Transport

Water samples were collected from Burnt Bridge Creek on the first Monday of each month between the hours of 7:00 a.m. and 9:00 a.m. Pacific time for a period of two years. A 1-L grab sample was collected by hand approximately six inches below the surface immediately upstream from the eastern boundary of the golf course (“entrance point”, Fig.1). A second grab sample was collected where the creek exited the southern boundary of the golf course (“exit point”, Fig.1). Results of the analyses of the exit point sample were compared to the entrance point sample to assess the influence of golf course management practices on surface water quality.

Samples for NO₃-N and orthophosphate analysis were collected in new, clean 250 ml polypropylene bottles that were sealed with new, plastic lids. Corresponding samples for pesticide testing were collected in new, certified clean, one-liter amber glass bottles sealed with teflon-lined lids. Following collection, samples were maintained at 4⁰C in a plastic cooler and transported to testing laboratories within 2-h of collection. Chain-of-custody was documented from the point of sample collection through the point of sample delivery to the testing laboratories.

Sample Analysis

Nitrate-N and Orthophosphate.

Samples were analyzed for nitrate-N and orthophosphate by North Creek Analytical (Beaverton, OR), a commercial laboratory accredited by the State of Washington Department of Ecology (DOE). All nitrate-N testing was performed within 48-h of sample collection according to EPA method 300.0 using ion exchange chromatography with a conductivity detection system, and a method reporting limit of 0.1 mg L⁻¹.

Table 2. Pesticide analytical methods and method reporting limits.

Method	a.i. common name	a.i. chemical name	MRL, $\mu\text{g L}^{-1}$
EPA 547	glyphosate	Isopropylene salt of N-(phosphonomethyl) glycine	20
EPA 608	propiconazole	1-[[2(2,4-dichlorophenyl)-4propyl-1,3,dioxolan-yl]methyl]-1H-1,2,3-triazole	0.040 - 0.12†
	iprodione	3-(3,5-dichlorophenyl)-N-(1-methylethyl)-2,4-dioxo-1-imidazolidinecarboxamide	0.060
	trifloxystrobin	E,E-alpha-(methoxylmino)-2[[[1-3[-trifluoromethyl] phenyl] ethylidene] amino] oxyl] methyl]-, methyl ester.	0.060
	chlorpyrifos	O,O-diethyl O-(3,5,6,-trichloro-2-pyridinyl) phosphorothioate	0.040-0.060†
	chlorothalonil	Tetrachloroisophthalonitrile	0.060
	PCNB	Pentachloronitrobenzene	0.040-0.060†
	flutolanil	3'-isopropoxy-2-(trifluoromethyl)benzanilide	0.60
	oxadiazon	5-tert-butyl-3-(2,4-dichloro-5-isopropoxyphenyl)-1,3,4-oxadiazol-2(3H)-one	0.060
EPA 615	clopyralid	3,6-dichloro-2-pyridinecarboxylic acid	0.080
	triclopyr	(3,5,6-trichloro-2-pyridinyloxy)acetic acid	0.080
	2,4-D	2,4-dichlorophenoxyacetic acid	0.20
	dicamba	3,6-dichloro-2-methoxybenzoic acid; 2,6-dichloro-o-anisic acid; 2-(2-amonoethoxy) ethanol salt of 3,6-dichloro-o-anisic acid	0.080
	mecoprop	Potassium (RS)-2-(2-methyl-4-chlorophenoxy) propionate	2.0 – 20†
EPA 625	triadimefon	1-(4-chlorophenoxy)-3-3-dimethyl-1-(1H,2,4-triazole-1-)-2-butanone	0.60
	fludioxinil	4-(2,2-difluoro-1,3-benzodioxol-4-yl)-1H-pyrrole-3-carbonitrile	0.12 – 0.80†
EPA 630.1	mancozeb	Manganese bisdithiocarbamate	10
EPA 632	azoxystrobin	Methyl (E)-2-2-6-(2-cyanophenoxy)pyrimidin-4-yloxy-phenyl-3-methoxyacrylate	0.60
	carbaryl	1-naphthyl methylcarbamate	0.030 - 0.25†
	bendiocarb	2,2-Dimethyl-1,3,-benzodioxol-4-yl methycarbamate	0.30
In-house	thiophanate-methyl	1,2-di-(3-methoxycarbonyl-2-thioureido) benzene; diethyl [1,2-phenylenebis (iminiocarbonothioyl)] bis[carbamate]	0.20 - 0.60†

† Method reporting limit sensitivity increased during the course of the study period due to method improvements or improvements in instrument sensitivity.

Orthophosphate testing was performed according to the colorimetric EPA method 365.2 using a photometric detector set at the 880 nm wavelength, and a method reporting limit of 0.01 mg L^{-1} . Quality assurance included a lab-blank, a lab-control sample, a lab-control sample duplicate, a lab-matrix spike, and a lab-matrix spike duplicate.

Paired samples with positive concentrations of nitrate-N and orthophosphate existed for every sample collection date. Data were analyzed using a two-tailed T-test to detect statistically significant differences between entry and exit point samples.

Pesticides.

Pesticide analysis was performed by Pacific Agricultural Laboratory (Portland, OR), a commercial pesticide analysis

laboratory accredited by the Washington DOE. Monthly pesticide analysis was based on the pesticide active ingredients applied to the golf course in the previous month. Samples were prepared for analysis within a seven-day hold time. Pesticide analyses were performed according to EPA methods, except for thiophanate-methyl which was analyzed by an in-house method. The analytical methods and respective method reporting limits for all pesticide active ingredients applied to the golf course are listed in Table 2.

For EPA method 547, quality assurance procedures included a lab-blank, a lab-fortified blank, and a lab-fortified matrix. For all remaining methods, quality assurance data included a lab-blank, a lab-control sample, and a lab-control sample duplicate. For all methods running batch control charts were

maintained that included matrix control spike results for the most recent 20 batch runs. Control limits included a method warning limit (2 standard deviations) and a method control action limit (3 standard deviations).

RESULTS

Yearly Temperature and Precipitation Patterns

The area climate is temperate with cool, wet winters and warm summers. The 116-yr average monthly minimum temperature was lowest in Jan (1.2°C) and the average monthly maximum temperature was highest in August (26.2°C). Average monthly temperature minima and maxima during the study were similar to the long term averages (Fig. 2).

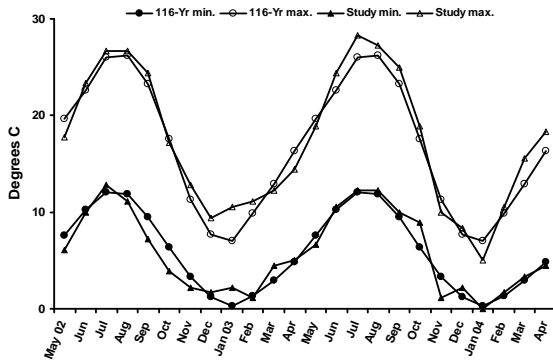


Figure 2. Mean monthly minimum and maximum temperatures at Vancouver, WA, USA, during study period, and 116-year means (1891 – 2007).

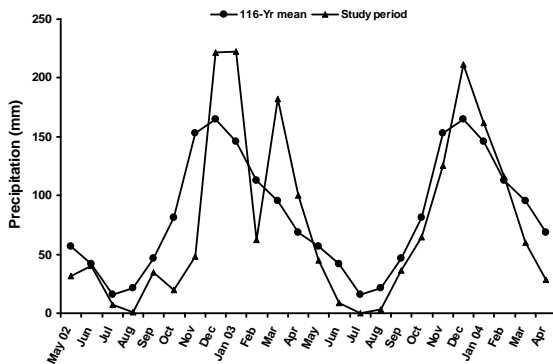


Figure 3. Monthly precipitation at Vancouver, WA, USA, during study period, and 116-year mean (1891 – 2007).

Total annual precipitation (116-yr mean) in Vancouver was 1,001 mm, with the highest monthly precipitation occurring in Dec (161 mm) and the lowest occurring in Jul (16 mm). For the study period, year one precipitation totaled 955 mm and was below normal in fall and above normal in winter and spring (Fig. 3). Total precipitation in year two was 861 mm and followed the 116-yr mean precipitation pattern (Fig 3.), except during Dec 2003, which was wetter than normal (212 mm).

Nutrient and Pesticide Transport Conditions

Most monthly fertilizer inputs occurred between May and Oct, months of relatively low precipitation (Fig. 3) and irrigation was the factor most likely to influence nutrient transport. However, some fertilizer inputs did occur during the rainy season of each year in which precipitation-driven transport conditions were favorable. For year one, fertilizer inputs during the winter consisted primarily of N alone, and tended to be confined to small areas of the golf course. However, six separate N inputs did occur during a comparatively rainy month (Apr 2003), including a major N input to fairways (445 kg, 50% slow release). The large fairway N application occurred 12 d prior to sample collection, and 40 mm of precipitation were recorded during the interval between application and sample collection. For year two, a large fairway N application (445 kg ammonium sulfate) occurred during Mar 2004, and 24.6 mm of precipitation were recorded in the 12 d interval between application and sample collection (Table 3).

The majority of fungicide and insecticide applications occurred during the rainy winter season. For year one, 13 fungicide applications, four insecticide applications, and two herbicide applications occurred between Dec and

Table 3. Fungicide and insecticide applications during precipitation-driven transport conditions.

Pesticide	Application		Prec. ‡	Mobility§	Soil Half-life (days)§	Water	
	Month/Year	Days†				Solubility (mg L ⁻¹)§	K _{oc} §¶
carbaryl	Dec 02	25	251	Low	10	120	300
	Mar 03	11	31				
chlorothalonil	Dec 03	28	185	Low	30	0.6	1,380
	Feb 04	11	49				
chlorpyrifos	Feb 03	27	64	Very Low	30	0.4	6,070
	Feb 03	5	5				
fludioxinil	Mar 03	21	103	Immobile#	6-25#	1.8#	12,000 – 392,000#
	Apr 03	10	22				
iprodione	Dec 02	14	130	Low	14	13.9	700
	Feb 03	5	5				
	Jan 04	13	94				
	Jan 04	12	94				
mancozeb	Feb 04	11	49	Low	70	6	2,000
	Jan 03	13	153				
PCNB	Feb 03	27	64	Very Low	21	0.44	5,000
	Mar 03	12	42				
	Mar 03	8	131				
	Apr 03	36	83				
	Nov 03	14	102				
propiconazole	Feb 04	11	49	Moderate	110	110	650
	Jan 03	13	153				
	Feb 03	27	64				
	Mar 03	21	103				
	Apr 03	10	22				
thiophanate-methyl	Dec 03	28	185	Very Low	10	3.5	1,830
	Dec 02	14	130				
	Feb 03	5	5				
	Dec 04	25	172				
	Jan 04	13	94				
Jan 04	12	94					

† Number of days between pesticide application and water quality monitoring sample collection.

‡ Measurable precipitation (millimeters) recorded in the interval between product application and water quality monitoring sample collection.

§ from Vogue et al., (1994).

¶ K_{oc} = Organic carbon partition coefficient.

from National Registration Authority for Agricultural and Veterinary Chemicals 2000.

Apr (Fig. 3). During year two, nine fungicide applications occurred between Nov and Feb (Fig. 3).

There were several instances during the study period in which conditions for precipitation-driven transport of fungicides and insecticides were favorable. Table 3 shows the interval between application and sample collection, and the corresponding post-application precipitation for all fungicide and insecticide applications between Dec 2002 through Apr 2003, and Nov 2003 through Feb 2004. During Dec

2002, 252 mm of precipitation were recorded during a 25 day interval following a carbaryl application and 130 mm of precipitation were recorded during a 14 day interval following an iprodione application. In Jan 2003, 153 mm of precipitation were recorded in the 13 day interval following mancozeb and propiconazole applications. Three fungicides differing in mobility and persistence properties (chlorothalonil, iprodione, and PCNB) were applied on the same day in Feb 2004 followed by 49 mm of precipitation during the 11 day interval preceding sample collection.

Nutrient Output Monitoring

Entrance point nitrate-N for both years was lowest during Jun and Jul and highest during Dec, when nitrate-N was three times higher than in corresponding Jun and Jul samples (Fig. 4). The seasonal variation in entrance point nitrate-N closely followed the precipitation pattern of the study period (Figs. 3, 4). Note dates in Fig. 4 lag one month behind those in Fig. 3. This is because sampling occurred early in the month (i.e., on the first Monday). The first monthly sample (Jun 2002) was therefore influenced mostly by weather conditions the preceeding May. For this reason, weather and water quality data are presented in this staggered manner. For 22 of the 24 monthly samples, nitrate-N in exit point samples was equal to or less than that in corresponding entrance point samples (Fig. 4).

Reduction in exit point nitrate-N was observed for 15 sampling events, and ranged from 0.1 mg L⁻¹ (n = 7) to 0.2 mg L⁻¹ (n = 8). For two sampling events (Dec 2003, Jan 2004) exit point nitrate-N was 0.1 mg L⁻¹ above that in matching entrance point samples. These increases were observed for months in which the amounts of nitrogen applied were very low, and did not appear to be related to fertilizer applications.

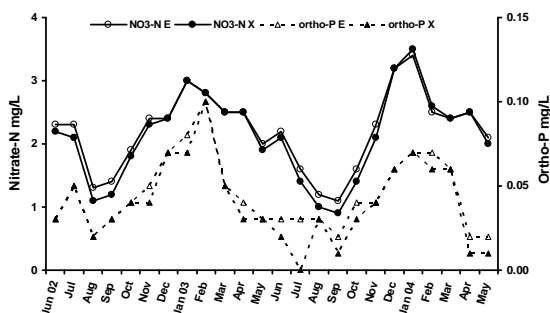


Figure 4. Nitrate-N and orthophosphate concentrations for paired entry (E) and exit (X) point samples collected from Burnt Bridge Creek at Royal Oaks Country Club, Vancouver, WA, USA, Jun 2002 – May 2004.

Entrance point orthophosphate concentrations followed the same seasonal pattern as nitrate-N during the study period, with concentrations highest during the winter months. Entrance point orthophosphate concentrations ranged from 0.02 mg L⁻¹ to 0.10 mg L⁻¹. For all sampling events, exit point orthophosphate was equal to or lower than corresponding entrance point samples (Fig. 4), with exit point concentrations being 0.01 mg L⁻¹ lower for nine sampling events, and 0.03 mg L⁻¹ lower in Jun 2003.

The nitrate-N and orthophosphate data for the study period were evaluated using a 2-tailed t-Test: paired two sample for means, with the null hypothesis equaling zero. Although the sample size (24 matched pairs) did not fully satisfy the requirements of the method ($n \geq 30$), the results of this analysis suggested that overall, exit point nitrate-N and orthophosphate concentrations were lower than those in corresponding entry point samples at a statistically significant level (nitrate-N, $P < 0.0005$; orthophosphate, $P < 0.003$).

Pesticide Output Monitoring

During the study period 104 a.i.-specific analyses were performed (53 in year one, and 51 in year two), and no fungicides or insecticides were detected in entrance point or exit point samples. The herbicide triclopyr was detected on one occasion (July 2002) at a concentration of 0.1 $\mu\text{g L}^{-1}$ in the exit point sample. The presence of triclopyr in this sample was confirmed by secondary gas chromatography. This detection was consistent with the application of a triclopyr-containing product (trade name = Confront) to border rough and green surrounds that occurred 6 d before sample collection.

DISCUSSION

The golf course evaluated during this study was well-suited for surface water

quality monitoring. The creek passing through the golf course was in close proximity to managed turf, and the topography and drainage system directed surface and subsurface water toward the creek. The combination of intensive turf management, the physical features of the golf course, and narrow sampling intervals optimized the potential to detect evidence of nutrient and/or pesticide transport into surface water.

No evidence of significant impacts on surface water quality from fertilizer applications was identified. Lack of detectable nutrient transport from the golf course may have been related to fertilizer applications occurring mainly during periods of maximum plant uptake and minimal runoff conditions. These observations are consistent with other research with turf systems. Ryals et al. (1998) monitored water quality in ponds on three North Carolina golf courses for one year. They concluded that there was no impact from golf course management practices on nutrient content in the ponds. Linde and Watschke (1997) observed that significant nutrient runoff was limited to times when fertilizer was applied shortly (8 h) before a simulated rainfall event. King et al. (2007) monitored nutrient content in a golf course stream in Texas during rain storm events for five years. They found significantly higher median nitrate-N and orthophosphate concentrations where the stream exited the course compared to where it entered. Mean concentrations were no different however. They did not collect samples during base flow (non-storm) conditions. Steinke et al. (2007) observed that most P runoff from turf occurred when the ground was frozen. These conditions rarely exist west of the Cascade Mountains in the Pacific Northwest where the present study was conducted. Stienke et al. (2007) concluded that turf may pose no more risk for P runoff than an unfertilized prairie.

Unlike fertilizer application conditions, a substantial proportion of pesticide applications occurred during periods that favored precipitation-driven transport. Most fungicide applications for both years occurred when precipitation was heavy and sustained; and for year one, two insecticide applications occurred during periods of heavy precipitation. In spite of frequent precipitation-driven transport conditions during the study, no fungicides or insecticides were detected in surface water exiting the golf course.

Of the 104 a.i.-specific pesticide analyses performed during the two-year period, only one pesticide (triclopyr) was detected, and was only detected in surface water exiting the golf course. The concentration of triclopyr detected ($0.1 \mu\text{g L}^{-1}$) was compared to toxicity data (Exttoxnet, 1993) for a variety of aquatic species (i.e., mallard ducks, rainbow trout, *Daphnia magna*). The results of this evaluation revealed that the level detected was over six orders of magnitude lower than the LC_{50} for the most sensitive species listed (rainbow trout = 117 mg L^{-1}), indicating that the concentration detected was not toxicologically significant. Similarly, Ryals et al. (1998) were unable to detect pesticides in outflows from ponds on golf courses. Pesticides were detected in the pond water, but at concentrations that were several orders of magnitude below median lethal concentrations for fish. They concluded that golf course management practices had no negative impacts on water quality.

CONCLUSION

Regardless of the fertilizer or pesticide product applied, the time of year, and individual product transport potential, intensive water quality monitoring failed to detect nutrient output or toxicologically significant pesticide output from the golf

course into surface water. Based on the results of this investigation, management practices used at this golf course, which were typical of high-maintenance golf courses in the Pacific Northwest, had no significant impact on surface water quality.

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