Phosphorus in Surface Runoff from Calcareous Arable Soils of the Semiarid Western United States

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ABSTRACT

Management strategies that minimize P transfer from agricultural land to water bodies are based on relationships between P concentrations in soil and runoff. This study evaluated such relationships for surface runoff generated by simulated sprinkler irrigation onto calcareous arable soils of the semiarid western United States. Irrigation was applied at 70 mm h^{-1} to plots on four soils containing a wide range of extractable P concentrations. Two irrigation events were conducted on each plot, first onto dry soil and then after 24 h onto wet soil. Particulate P (>0.45 μm) was the dominant fraction in surface runoff from all soils and was strongly correlated with suspended sediment concentration. For individual soil types, filterable reactive P (<0.45 μm) concentrations were strongly correlated with all soil-test P methods, including environmental tests involving extraction with water (1:10 and 1:200 soil to solution ratio), 0.01 *M* $CaCl_2$, and iron strips. However, only the Olsen-P agronomic soil-test procedure gave models that were not significantly different among soils. Soil chemical differences, including lower $CaCO_3$ and water-extractable Ca, higher water-extractable Fe, and higher pH, appeared to account for differences in filterable reactive P concentrations in runoff from soils with similar extractable P concentrations. It may therefore be possible to use a single agronomic test to predict filterable reactive P concentrations in surface runoff from calcareous soils, but inherent dangers exist in assuming a consistent response, even for one soil within a single field.

Phosphorus transfer in runoff from agricultural soils to water bodies can contribute to blooms of toxin-producing cyanobacteria (blue-green algae) and other water quality problems associated with eutrophication (Foy and Withers, 1995; Leinweber et al., 2002). Accumulation of P in soils occurs following long-term application of manure or mineral fertilizer in excess of crop requirements, and a growing number of studies show strong correlations between concentrations of extractable soil P and filterable reactive P in runoff (for recent reviews see Haygarth and Jarvis, 1999; Sims et al., 2000). Linear relationships were observed in surface runoff (Pote et al., 1996, 1999), while studies of subsurface drainage under natural rainfall can display nonlinear relationships, whereby filterable reactive P concentrations increase markedly after exceeding a threshold or "change point" in extractable soil P (e.g., Hesketh and Brookes, 2000). Understanding these relationships will contribute to the development of models and management practices aimed at reducing the risk of P transfer (Sharpley et al., 2002).

To overcome the inherent variability associated with natural rainfall events, several studies used simulated rainfall to investigate relationships between extractable soil P and P concentrations in surface runoff (Ketcheson and Onderdonk, 1973; Timmons et al., 1973; Romkens and Nelson, 1974; Wendt and Corey, 1980). This approach was improved recently by the adoption of a standardized rainfall simulator and experimental protocol, which enables comparison of results from different research groups (Humphry et al., 2002). Recent rainfall simulation studies reported strong correlations between extractable soil P and filterable reactive P in runoff for tilled soils (Andraski and Bundy, 2003), acidic pasture soils with relatively high organic matter concentrations (Pote et al., 1996, 1999), and calcareous clay soils under pasture (Torbert et al., 2002). Other studies demonstrated that such relationships are masked by recent manure additions (Kleinman et al., 2002) and that filterable reactive P concentrations in runoff can be decreased by treating manure with alum products (Smith et al., 2001).

Despite the extensive work linking extractable soil P with P concentrations in surface runoff, there is currently little information on relationships for irrigated arable soils of the semiarid western United States, which typically contain considerable concentrations of $CaCO_3$ and relatively small concentrations of organic C (<10 g kg^{-1}). Such soils are agronomically important, because irrigated agriculture produces nearly 40% of the total U.S. crop value from only 15% of the total cropped land (Bajwa et al., 1992). Much of this land is irrigated by sprinkler systems; for example, in the Pacific Northwest about two-thirds of the irrigated land (1.7 million ha) is irrigated by sprinkler systems, 32% by gravity flow systems, and the rest by drip or other irrigation methods (USDA National Agricultural Statistics Service, 1999). Our aim was to determine relationships between selected soil P extractants and P concentrations in surface runoff generated by sprinkler irrigation on tilled calcareous soils of the semiarid western United States.

MATERIALS AND METHODS

Locations and Experimental Treatments

Experiments were conducted on soils where plots with a range of soil-test P concentrations were previously established by addition of manure or chemical fertilizer (Robbins et al., 2000; Table 1). All soils had slightly alkaline pH and contained various amounts of $CaCO_3$ (22–245 g kg^{-1}). The Portneuf soil (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids) and Greenleaf soil (fine-silty, mixed, superactive, mesic Xeric Calciargids) were silt loams, while the War-

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Table 1. Site details and soil properties for soils to a 30-cm depth.

	Soil			
Characteristic	**Portneuf topsoil**	**Portneuf subsoil**	**Warden**	**Greenleaf**
Location	**Kimberly, ID**	**Kimberly, ID**	**Prosser, WA**	**Parma, ID**
Texture	**silt loam**	**silt loam**	**very fine sandy loam**	**silt loam**
Mean annual temperature, °C	**8.7**	**8.7**	**10.1**	**10.2**
Mean annual rainfall, mm	**275**	**275**	**209**	**260**
Treatment	**organic and mineral fertilizers**	**organic and mineral fertilizers**	**mineral fertilizer**	**mineral fertilizer**
Sand, g kg^{-1}	**180**	**170**	**490**	**280**
Silt, g kg^{-1}	**570**	**660**	**410**	**490**
Clay, g kg^{-1}	**250**	**170**	**100**	**230**
$CaCO_3$, g kg^{-1}	**118†**	**245†**	**22‡**	**120‡**
Organic C, g kg^{-1}	**9.3†**	**7.0†**	**5.4‡**	**5.9‡**
pH	**8.0**	**8.1**	**8.1‡**	**7.7‡**

† Values for $CaCO_3$ and organic C for the Portneuf soils are mean values for the eight plots (Westermann et al., 2001).

‡ Values for $CaCO_3$, organic C, and pH in the Warden and Greenleaf soils are taken from Turner et al. (2003), except for $CaCO_3$ in the Greenleaf soil due to a difference in the field used for irrigation simulation experiments.

den soil (coarse-silty, mixed, superactive, mesic Xeric Haplocambids) was a fine sandy loam. The Portneuf soil included standard topsoil plots, plus plots where the surface 30 cm of soil was removed to simulate the effect of erosion by long-term furrow irrigation exposing the highly calcareous subsoil (Robbins et al., 2000). This subsoil is termed a soil type for simplicity. The climate of the locations is semiarid, with hot, dry summers and cool, moist winters (Table 1). All experiments were conducted on bare, tilled soils between May and September 2002.

Sprinkler Irrigation Simulation

Sprinkler irrigation was generated using a standardized simulator and experimental protocol (Humphry et al., 2002). Briefly, the simulator was constructed from Al pipe with a single HH 50 WSQ nozzle (Spraying Systems, Wheaton, IL) 3 m above the center of the plot. Irrigation was applied at 70 mm h^{-1} onto adjacent duplicate subplots (1 m wide × 2 m long) isolated by steel frames inserted into the ground to a 5-cm depth, leaving a 5-cm border above the surface to contain runoff. Surface runoff was channeled to a collection point after passing over a lip placed level with the soil surface at the downslope end of the frame. The soil was lightly tilled with a rake to even the surface before irrigation. Runoff was generated twice on each plot, first on soils at field moisture (moisture content 2–5%), then on the same plots after 24 h (moisture content 17–29%). Irrigation water was generated by reverse osmosis and supplied from a portable 1000-L tank. The water had an electrical conductivity of 7.0 μS cm^{-1}, with mean concentrations (n = 16) of elements (mg L^{-1}) determined by inductively coupled plasma–optical emission spectrometry (ICP–OES) being: Ca 0.43 ± 0.14, Fe 0.010 ± 0.008, K 0.14 ± 0.07, Mg 0.10 ± 0.04, Na 1.18 ± 0.36, P 0.002 ± 0.005, and Si 0.37 ± 0.12.

The plots were irrigated until 30 min of continuous runoff was collected. Samples of runoff water were collected separately from both subplots at 5-min intervals from the onset of runoff (determined as continuous flow of water from the collection points). Total runoff was also collected from each subplot in 12-L drums, with 1-L portions from each drum placed in Imhoff cones to determine suspended sediment concentration (Sojka et al., 1992). Samples for P analysis were collected separately in 60-mL plastic bottles. A portion of each sample (30 mL) was immediately filtered in the field through a 0.45-μm cellulose-nitrate membrane (Millipore Corp., Billerica, MA) and returned on ice to the laboratory. We consider immediate filtration essential when even a small concentration of suspended sediment is present, because filterable reactive P concentrations can increase rapidly in unfiltered samples due to continual phosphate desorption from suspended sediment (Jarvie et al., 2002).

Analytical fractions determined on filtered samples are termed "filterable" rather than "soluble" or "dissolved," because runoff from the soils studied here contains a continuum of colloidal particles associated with P (Turner et al., 2004). Total P in unfiltered samples was determined by persulfate digestion using a procedure slightly modified from that described by Rowland and Haygarth (1997) to include centrifugation (3000 × g for 10 min) of digested samples to remove residual particulates. This procedure may, however, underestimate total P concentrations in samples containing high concentrations of suspended sediment (Jarvie et al., 2002). Reactive P, which approximates free phosphate, was determined in filtered samples by molybdate colorimetry (Murphy and Riley, 1962) using a 12-min reaction time to minimize acid-induced hydrolysis of labile organic and colloidal P. Total filterable P was determined by ICP–OES. Filterable unreactive P, which includes organic P, inorganic polyphosphate, and acid-resistant colloidal P, was the difference between total P and reactive P in filtered samples.

Runoff from the Portneuf soil was analyzed for reactive P and total elements within 6 h of collection. Runoff from the other soils was stored at 4°C and analyzed within 7 d. We considered this longer storage time acceptable given the relatively high ionic strength of the samples, which minimizes sorption of reactive P to vessel walls (Jarvie et al., 2002). Total P in unfiltered samples was determined after storage at 4°C for approximately three months.

Soil Sampling and Analysis

Soil samples were taken from both subplots before each irrigation (dry and wet soils). Six portions of soil were taken from the top 2 to 3 cm and combined to produce a single bulked sample for each subplot. These were analyzed separately and subplots were averaged to produce a single value for each plot. Sampling from the surface of the plots was unlikely to influence their hydrology due to the shallow sampling depth and the tilled nature of the soils. All soil samples were air-dried at 30°C for 7 d and stored at ambient laboratory temperature for three months before analysis.

Soil samples were analyzed by five soil-test P procedures. Olsen P was determined by extraction with 0.5 M $NaHCO_3$ (adjusted to pH 8.5) for 30 min in a 1:20 soil to solution ratio (Olsen et al., 1954). Each extract was filtered through a Whatman (Maidstone, UK) no. 42 filter paper before analysis. Water-extractable P (deionized water) was determined in two soil to solution ratios (1:10 and 1:200); samples were shaken for 1 h and centrifuged at 3000 × g for 15 min. Calcium chloride–extractable P was determined by extraction in 0.01 *M* $CaCl_2$ for 1 h in a 1:10 soil to solution ratio. Both water and $CaCl_2$ extracts were filtered through 0.45-μm cellulose-nitrate membranes before analysis. Iron strip–extractable P was determined following the method described by Sharpley (1993). In all procedures, extractions were conducted at 20°C and reactive P was determined by colorimetry (Murphy and Riley, 1962). Water extracts were also analyzed for cations by ICP–OES.

Soil pH was determined in a 1:2 soil to deionized water mixture and moisture content was determined by drying a 100-g soil sample at 105°C for 24 h. Organic C concentrations were determined by dichromate digestion (Nelson and Sommers, 1982) and $CaCO_3$ concentrations by acid titration (Allison and Moodie, 1965).

Statistical Analysis

For each irrigation event, runoff volume, P concentrations, and suspended sediment concentrations were averaged for each 5-min sample from the duplicate plots. Flow-weighted mean P and sediment concentrations were then calculated using concentration and flow volume data. Statistical differences in regression models describing the relationship between extractable soil P and filterable reactive P in runoff for the first and the second runs (dry and wet soils, respectively) were evaluated using procedures described by Neter and Wasserman (1974) to indicate significant differences in slopes and intercepts. The same procedure was then used to investigate the significance of differences between regression models of different soils using pooled data from the dry and wet runs.

RESULTS

Soil-Test Phosphorus Concentrations

Concentrations of reactive P extracted by the five soil-test P procedures are shown in Table 2. Greatest concentrations were extracted by the Olsen and Fe-strip procedures, with smaller concentrations extracted by water and $CaCl_2$. The wider soil to solution ratio (1:200) extracted much greater amounts of P than the narrower ratio (1:10). Differences in soil-test P concentrations between the first and second runs were relatively minor, although a trend toward smaller concentrations in wet soils was apparent for several extractants, notably for the Warden sandy loam. The different extraction procedures were strongly correlated with each other, with *r* values of >0.95 for many relationships (Table 3). Exceptions were correlations between Fe-strip extracts and all other tests for the Greenleaf soil, and for Olsen P and water extracts (1:10 ratio) of the Portneuf topsoil.

Table 3. Correlation coefficients (*r* values) for relationships among extractable soil P concentrations determined using five soil-test P procedures.†

	Water (1:10)‡	Water (1:200)§	$CaCl_2$ (1:10)‡	Iron strip
		Portneuf topsoil		
Olsen	0.55	0.81*	0.88**	0.91**
Water (1:10)		0.94***	0.87**	0.64
Water (1:200)			0.98***	0.83*
$CaCl_2$ (1:10)				0.84**
		Portneuf subsoil		
Olsen	0.96***	0.99***	0.95***	0.84**
Water (1:10)		0.98***	0.99***	0.79*
Water (1:200)			0.96***	0.85**
$CaCl_2$ (1:10)				0.74*
		Warden		
Olsen	0.99***	0.98***	1.00***	0.99***
Water (1:10)		0.99***	0.98***	0.97***
Water (1:200)			0.97***	0.95***
$CaCl_2$ (1:10)				1.00***
		Greenleaf		
Olsen	0.96***	0.99***	0.99***	−0.45
Water (1:10)		0.97***	0.99***	−0.18
Water (1:200)			0.99***	−0.40
$CaCl_2$ (1:10)				−0.31

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Data are from soils sampled before irrigation events on dry and wet soil.

‡ Extracted in a 1:10 soil to solution ratio.

§ Extracted in a 1:200 soil to solution ratio.

Unreactive P concentrations in the extracts were small. For example, Olsen unreactive P concentrations (mg P kg^{-1} dry soil) for the four soils averaged 4.4 (Portneuf topsoil), 4.9 (Portneuf subsoil), 1.3 (Warden) and 1.9 (Greenleaf) (data not shown).

Runoff Phosphorus and Sediment Concentrations

Flow-weighted mean total P concentrations in unfiltered runoff samples were >1 mg P L^{-1} for all four soils, with concentrations up to 20 mg P L^{-1} recorded from the Portneuf subsoil (Table 4). Most of the total P was particulate (>0.45 μm) P associated with the relatively large concentrations of suspended sediment

Table 2. Soil-test P concentrations for four calcareous soils used in irrigation experiments.

Extractant	Soil†	Portneuf topsoil (*n* = 8)	Portneuf subsoil (*n* = 8)	Warden soil (*n* = 7)	Greenleaf soil (*n* = 4)
		mg P kg^{-1} dry soil			
Olsen	dry	20–104 (41)‡	28–137 (74)	11–101 (36)	4–8 (6)
	wet	20–97 (40)	29–136 (73)	9–87 (31)	4–7 (5)
Water (1:10)§	dry	1.3–10.1 (5.3)	0.4–8.5 (2.9)	2.5–27.4 (10.8)	0.2–1.7 (0.8)
	wet	2.6–11.1 (6.1)	0.6–11.1 (4.2)	2.2–24.3 (9.1)	0.4–1.8 (1.0)
Water (1:200)¶	dry	12.7–40.0 (22.4)	6.8–43.5 (21.5)	6.0–77.9 (28.7)	1.8–6.0 (3.7)
	wet	14.2–37.8 (22.1)	6.8–41.0 (20.3)	5.5–64.7 (21.1)	1.8–5.8 (3.6)
$CaCl_2$ (1:10)§	dry	0.8–4.5 (1.8)	0.3–4.8 (1.6)	0.3–15.9 (4.3)	<0.1–0.3 (0.2)
	wet	0.8–4.1 (1.7)	0.3–4.7 (1.6)	0.2–12.1 (2.9)	<0.1–0.3 (0.2)
Fe strip	dry	44–99 (63)	46–107 (80)	41–168 (73)	26–39 (32)
	wet	41–90 (55)	42–118 (82)	36–159 (69)	29–36 (33)

† Samples (2–3 cm) were taken before two irrigation experiments on dry and wet soils. Soils were air-dried (30°C) for 7 d before analysis.

‡ Values are the range of concentrations for each soil, with the mean values in parentheses.

§ Extracted in a 1:10 soil to solution ratio.

¶ Extracted in a 1:200 soil to solution ratio.

Table 4. Flow-weighted mean P and sediment concentrations in runoff following irrigation onto four calcareous soils.

	Soil†	Portneuf topsoil	Portneuf subsoil	Warden soil	Greenleaf soil
		Concentrations			
Sediment, g L^{-1}	dry	0.7–7.4 (3.6)‡	2.7–7.1 (4.7)	1.1–3.5 (2.4)	0.8–2.3 (1.7)
	wet	1.0–7.8 (4.5)	1.8–9.2 (5.4)	1.0–4.3 (3.2)	0.7–1.6 (1.3)
Total P, mg P L^{-1}	dry	1.62–12.04 (5.93)	7.50–14.57 (10.64)	0.53–2.75 (1.51)	1.42–2.32 (1.86)
	wet	2.74–11.50 (7.57)	8.27–20.45 (11.89)	0.77–4.89 (2.78)	1.02–2.35 (1.81)
Particulate P, mg P L^{-1}	dry	1.52–11.81 (5.69)	7.52–13.91 (10.17)	0.51–2.58 (1.44)	1.38–2.30 (1.83)
	wet	2.65–11.33 (7.37)	8.15–19.91 (11.65)	0.73–4.66 (2.69)	0.98–2.32 (1.78)
Total filterable P, mg P L^{-1}	dry	0.097–0.358 (0.238)	0.100–0.655 (0.290)	0.028–0.167 (0.067)	0.025–0.046 (0.034)
	wet	0.091–0.306 (0.197)	0.074–0.530 (0.236)	0.035–0.235 (0.086)	0.026–0.041 (0.033)
Filterable reactive P, mg P L^{-1}	dry	0.092–0.341 (0.225)	0.084–0.651 (0.271)	0.025–0.167 (0.065)	0.023–0.046 (0.033)
	wet	0.087–0.287 (0.183)	0.068–0.532 (0.220)	0.027–0.235 (0.082)	0.025–0.037 (0.031)
Filterable unreactive P, mg P L^{-1}	dry	0.001–0.041 (0.014)	0.004–0.046 (0.020)	0–0.006 (0.002)	0–0.002 (0.001)
	wet	0.005–0.031 (0.016)	0.003–0.032 (0.017)	0–0.010 (0.004)	0–0.004 (0.002)
		Loads			
Sediment, kg ha^{-1} 30 min^{-1}	dry	104–1825 (670)	693–2051 (1344)	112–301 (239)	197–596 (451)
	wet	208–2397 (1160)	491–3210 (1721)	261–1193 (871)	239–503 (394)
Total P, kg P ha^{-1} 30 min^{-1}	dry	0.26–2.95 (1.15)	1.89–4.23 (2.99)	0.07–0.31 (0.15)	0.34–0.62 (0.50)
	wet	0.58–3.74 (2.35)	2.33–6.11 (3.79)	0.19–1.38 (0.76)	0.34–0.71 (0.56)
Filterable reactive P, kg P ha^{-1} 30 min^{-1}	dry	0.02–0.08 (0.04)	0.03–0.19 (0.08)	<0.01–0.02 (<0.01)	<0.01–0.01 (<0.01)
	wet	0.02–0.09 (0.05)	0.02–0.16 (0.07)	<0.01–0.07 (0.02)	<0.01–0.01 (0.01)
		Runoff variables			
Runoff volume, % irrigation applied	dry	36–65 (48)	63–87 (76)	21–35 (28)	63–76 (71)
	wet	56–83 (76)	65–96 (85)	67–76 (72)	80–89 (84)
Time to runoff, min	dry	6–18 (12)	4–9 (6)	17–22 (20)	7–14 (9)
	wet	1–5 (3)	2–4 (3)	1–4 (2)	4–8 (6)

† Data are from two irrigation experiments on dry and wet soil.

‡ Values are the range of concentrations for each soil, with the mean values in parentheses.

(average flow-weighted mean values between 1.3 and 5.4 g L^{-1} for the four soil types; Table 4). Particulate P and suspended sediment concentrations were strongly correlated (r = 0.60–0.88, $P < 0.05$; Fig. 1) and tended to be greater in runoff from the second irrigation event onto wet soil (Table 4). This was almost certainly due to greater runoff volumes during the second irrigation event, notably for the Warden soil. Time from the start of irrigation to the start of runoff was much shorter for the second event, which along with the total runoff volume, appeared to be influenced by antecedent moisture conditions (e.g., for Portneuf soils; Fig. 2).

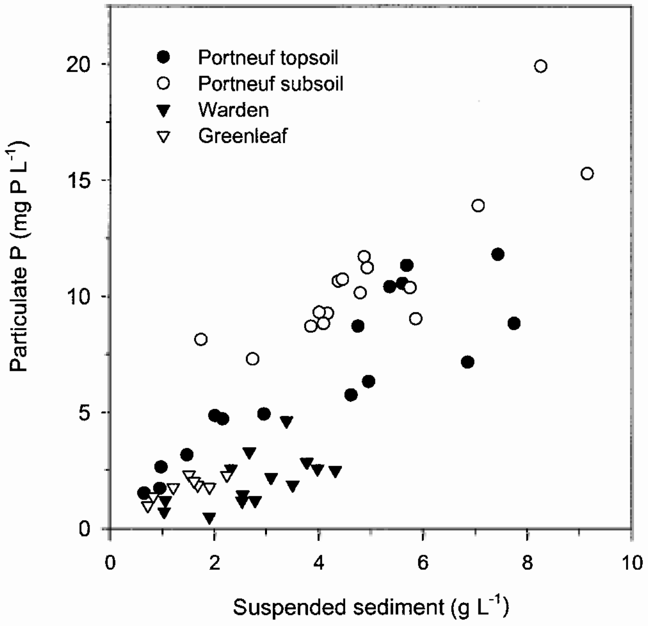

Fig. 1. Relationships between concentrations of particulate P (mg P L^{-1}) and suspended sediment (g L^{-1}) in surface runoff from four calcareous soils. Data are for two irrigation experiments on dry and wet soils. Portneuf topsoil: $Y = 1.25x + 1.52$, $r^2 = 0.77$, $F = 48.0$, $P < 0.001$. Portneuf subsoil: $Y = 1.42x + 3.77$, $r^2 = 0.73$, $F = 37.7$, $P < 0.001$. Warden soil: $Y = 0.67x + 0.19$, $r^2 = 0.36$, $F = 6.7$, $P < 0.05$. Greenleaf soil: $Y = 0.70x + 0.77$, $r^2 = 0.66$, $F = 11.7$, $P < 0.05$.

Flow-weighted mean filterable reactive P concentrations in runoff were <1 mg P L^{-1} for all soils and constituted only a small fraction of the total P in unfiltered samples (Table 4). Concentrations were always greatest in the initial runoff samples of each irrigation event and tended to be greater following irrigation on dry soil (Fig. 3). Filterable unreactive P concentrations in runoff were relatively small, with mean values of ≤0.02 mg P L^{-1} from all soils.

Relationships between Soil-Test Phosphorus and Filterable Reactive Phosphorus in Surface Runoff

For individual soil types, strong correlations existed between filterable reactive P concentrations in runoff and all soil-test P methods (Table 5, Fig. 4). The exception was Fe-strip P for the Greenleaf soil. Regression models were similar for the first (dry soil) and second (wet soil) runs, with significant differences in slopes detected only for the Portneuf subsoil ($CaCl_2$ and 1:10 ratio water extracts; $P < 0.05$) and the Warden soil (all soil-test P methods; data not shown). A nonlinear relationship between Olsen P and filterable reactive P in surface runoff may exist for the Portneuf subsoil (Fig. 4).

When all soils were considered together, only regression models for Olsen P were not significantly different. In contrast, models for "environmental" P tests (water and $CaCl_2$ extracts) were significantly different for all soils except the Greenleaf ($P < 0.001$); clearly, the narrow range of soil-test P concentrations for the Greenleaf

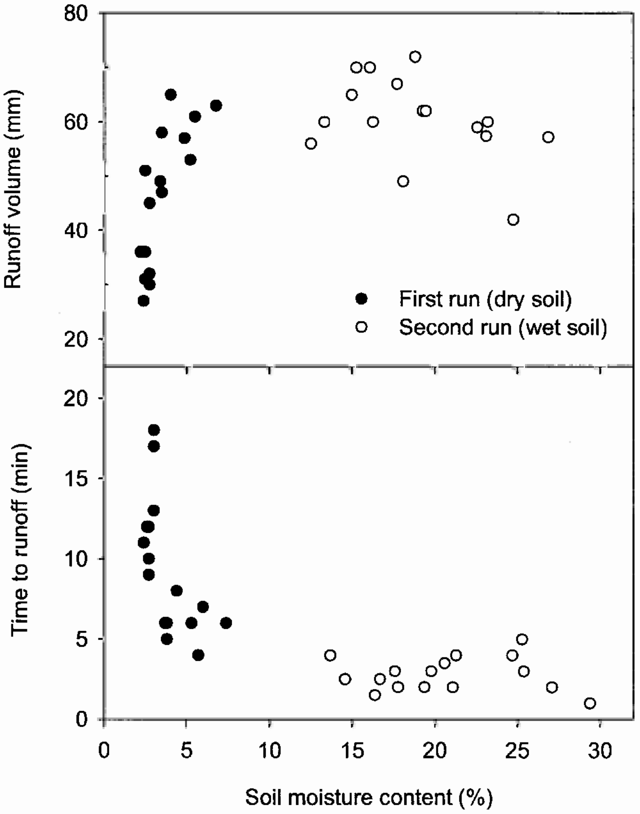

Fig. 2. Relationships between soil moisture content (%) and the total runoff volume (mm) and time from the start of irrigation to the start of runoff (min) for the Portneuf topsoil and subsoil plots. Data are from two irrigation experiments on dry and wet soils.

soil had a marked influence on the regressions. For Fe-strip P, only regression models for the Warden soil were significantly different. Differences in regression models remained statistically insignificant when filterable reactive P concentrations were normalized for runoff volume (Pote et al., 1999).

DISCUSSION

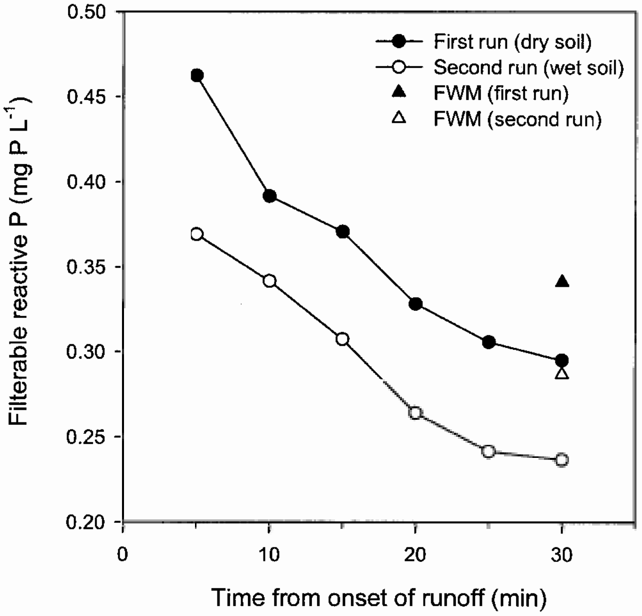

Fig. 3. Chemograph of filterable reactive P concentrations in surface runoff during a typical irrigation event. The data are from a plot on the Portneuf topsoil with an Olsen-P concentration of 46 mg P kg^{-1} dry soil. Data from two irrigation experiments on dry and wet soils are shown, with flow-weighted mean (FWM) concentrations indicated by single points.

The rainfall simulation protocol used here was designed originally to simulate intense natural rainfall. However, it may also be used to simulate center-pivot sprinkler irrigation, since application intensities up to 80 mm h^{-1} are common under the outer ends of some systems. The results presented here differ markedly from those obtained in furrow irrigation experiments on the same Portneuf topsoil and subsoil plots (Westermann et al., 2001). Particulate and filterable reactive P concentrations in furrow irrigation were both much smaller than those measured in the current study, and filterable reactive P concentrations were only weakly correlated to extractable soil P concentrations. This was almost certainly due in part to limited interaction between furrow irrigation water and soil particles, because relatively small concentrations of suspended sediment were generated in furrow irrigation experiments. The furrow irrigation study also used water from the Snake

Table 5. Regression models for relationships between soil-test P concentrations (*x*) and flow-weighted mean filterable reactive P concentrations in runoff (*Y*).†

	Portneuf topsoil (n = 8)	Portneuf subsoil (n = 8)	Warden soil (n = 7)	Greenleaf soil (n = 4)
Olsen	$Y = 0.002x + 0.117$; r^2 = 0.33**ad‡	$Y = 0.005x - 0.094$; r^2 = 0.93***bc	$Y = 0.002x + 0.007$; r^2 = 0.88***ab	$Y = 0.005x + 0.005$; r^2 = 0.90***cd
Water (1:10)§	$Y = 0.024x + 0.067$; r^2 = 0.70***a	$Y = 0.047 + 0.079$; r^2 = 0.78***b	$Y = 0.007x + 0.003$; r^2 = 0.86***c	$Y = 0.012x + 0.022$; r^2 = 0.79**abc
Water (1:200)¶	$Y = 0.009x + 0.012$; r^2 = 0.75***a	$Y = 0.015x - 0.059$; r^2 = 0.92***b	$Y = 0.002x + 0.016$; r^2 = 0.79***c	$Y = 0.005x + 0.016$; r^2 = 0.91***abc
$CaCl_2$ (1:10)§	$Y = 0.061x + 0.098$; r^2 = 0.63***a	$Y = 0.114x + 0.068$; r^2 = 0.95***b	$Y = 0.011x + 0.032$; r^2 = 0.80***c	$Y = 0.069x + 0.022$; r^2 = 0.83**abc
Iron strip	$Y = 0.004x - 0.033$; r^2 = 0.61***a	$Y = 0.006x - 0.235$; r^2 = 0.61***a	$Y = 0.001x - 0.026$; r^2 = 0.90***b	$Y = -0.001x + 0.053$; r^2 = 0.10 NS ab

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Models are derived from pooled data from two irrigation experiments on each plot (dry and wet soils).
‡ Models for different soils within each soil-test P procedure that have the same lowercase letter have slopes that are not significantly different at the 0.05 probability level.
§ Extracted in a 1:10 soil to solution ratio.
¶ Extracted in a 1:200 soil to solution ratio.

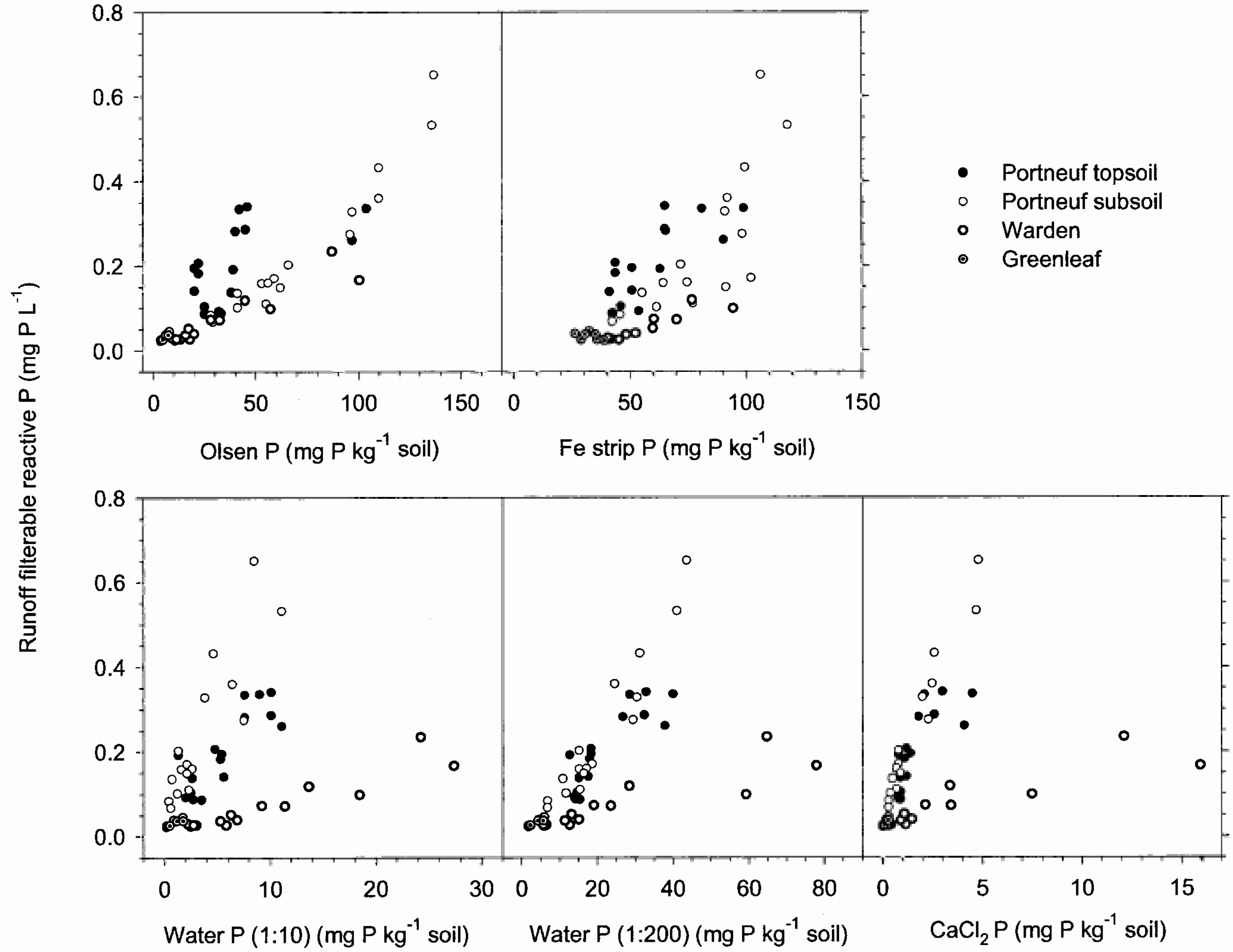

Fig. 4. Relationships between soil-test P concentrations (mg P kg^{-1} dry soil) and filterable reactive P concentrations in runoff (mg P L^{-1}). Data from two irrigation experiments on dry and wet soils are included.

River, which has a higher ionic strength from divalent soluble salts than the reverse osmosis water used in the current study. Particulate P is, however, more easily controlled than filterable reactive P. For example, polyacrylamide use in sprinkler irrigation systems markedly reduces total P and suspended sediment concentrations in surface runoff from irrigated fields (Bjorneberg et al., 2000).

Soils from the Portneuf topsoil and subsoil plots were further investigated to determine if soil chemistry could explain the differences in filterable reactive P. Four of the topsoil plots had pH values more than 0.2 units higher than other Portneuf topsoil and subsoil plots, and contained greater concentrations of water-extractable Al and Fe, but lower concentrations of $CaCO_3$– and water-extractable Ca and Mg (Fig. 5). Runoff from these plots also contained greater concentrations of Al and Fe (data not shown) than the other topsoil plots, and concentrations of filterable reactive P in surface runoff were greater than expected based on their extractable P concentrations. The four plots were all located in a small area of the field, but there was no indication from past management history to explain the differences in soil chemistry. The relatively low ionic strength of the source water may have been a factor in the apparent greater P solubility, because the plots did not give anomalous results in furrow-irrigated experiments using relatively high ionic strength Snake River irrigation water (Westermann et al., 2001). However, a previous laboratory study of the Portneuf soil under simulated sprinkler irrigation detected no significant effect of source water on filterable reactive P concentrations in runoff (Aase et al., 2001). It therefore seems likely that observed chemical differences increased P solubility from some plots, although how this interaction occurred is mechanistically unclear. Colloidal particles may certainly have been important, because we detected large proportions of colloidal P in filtered surface runoff from several of the soils analyzed in the current study (Turner et al., 2004). Most colloidal P was associated Ca and Mg in low molecular weight compounds, but runoff was not analyzed from the four plots with greater water-extractable Al and Fe concentrations. It therefore remains possible that colloidal Al and Fe particles contributed to the apparent greater P solubility in these plots.

All five soil-test P procedures, including agronomic

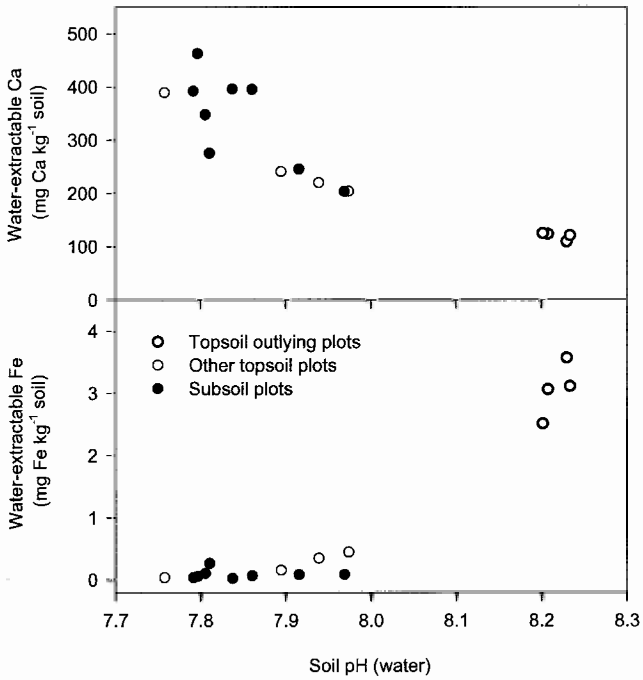

Fig. 5. Relationships between soil pH (1:1 soil to water ratio) and water-extractable Ca (top) and Fe (bottom) (mg kg^{-1} dry soil) for the Portneuf soil plots, highlighting the Portneuf topsoil plots that appeared elevated in the relationship between Olsen P and filterable reactive P in surface runoff (Fig. 4). Water-extractable elements were determined by extraction with deionized water for 1 h in a 1:10 soil to solution ratio.

and environmental tests, were strongly correlated to filterable reactive P concentrations in surface runoff for individual soils, but relationships were less clear for environmental tests when several soils were considered together. This may be partly linked to differences in soil chemical properties, but is more likely due to hydrological differences linked to soil texture: the Warden soil was a sandy loam, while the others were silt loams. A similar phenomenon was reported for a range of other soil types and management conditions (Sharpley, 1995; Pote et al., 1999; Torbert et al., 2002; Andraski and Bundy, 2003). For example, Andraski and Bundy (2003) observed steeper slopes in relationships between soil-test P and filterable reactive P in runoff for silty clay soils compared with silt loams, while Sharpley (1995) reported that Oklahoma soils with similar soil-test P concentrations yielded widely different filterable reactive P concentrations in runoff. This suggests that models using soil-test P concentrations to predict filterable reactive P concentrations in runoff are soil specific, which limits their value for agricultural P management. Pote et al. (1999) reported that normalizing filterable reactive P concentrations with runoff volume data eliminated differences in regression models between acidic pasture soils with different texture. However, the same procedure did not eliminate statistical differences in the regression models for the four soil types in the current study. The slight differences in soil-test P concentrations between dry and wet soils were previously reported for a range of soils (e.g., Turner and Haygarth, 2003) and did not greatly influence correlations with filterable reactive P in surface runoff in the current study.

Despite differences in relationships between soils for environmental tests, the Olsen test gave close agreement between the four soils. This is potentially important, because Olsen P is the predominant agronomic test for predicting P fertilization requirements for crop production in the western United States. Despite this, it is unclear how this can be applied to agricultural P management. Soil P accumulation clearly increases filterable reactive P concentrations in surface runoff, but it will be difficult to predict soil-test P concentrations above which this becomes an environmental concern. In particular, there are important scaling issues that remain to be resolved, because it is unclear how filterable reactive P concentrations measured in surface runoff in the field translate to catchment scales (Haygarth et al., 2004). "Change points" in soil P solubility offer a quantifiable and defensible threshold of environmental risk, but are potentially misleading because P concentrations in runoff from soils below the extractable soil P threshold may still threaten water quality. The use of a single predictive relationship is further confounded by changes in soil chemical properties within small distances. Future research should focus on better understanding how chemical properties influence P solubility in soil and runoff and attempt to link P export from field edges to impacts in the wider catchment.

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