FINAL REPORT

Relationship Between Soil and Runoff Phosphorus for Three Typical Iowa Soils A Component of the National Phosphorus Runoff Project

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INTRODUCTION

Understanding relationships between soil P and surface runoff P is important to assess the risk of P delivery from fields to surface water. Phosphorus loss to water resources with surface runoff is influenced by several factors including soil and water P concentration, rainfall intensity and duration, field slope, soil type, surface and subsurface hydrology, and proximity to water bodies among others. Further investigation was needed to understand relationships between soil P and P loss with surface runoff for different soil series. A group of scientists nucleated in the National P Runoff Project developed a coordinated effort to characterize these relationships for typical and important USA agricultural soils based on a standardized field rainfall simulation technique. The main objective of this project was to assess relationships between soil P and surface runoff P for three typical Iowa soils using the standardized rainfall simulation protocol suggested by the National P Runoff Project. Secondary objectives were to assess these runoff P relationships in soils with or without a history of manure application, with corn or soybean crop residue, and with simulated rainfall applied in the spring or fall seasons. This summary report highlights the major results of the study because data management for some relationships of interest continues at this time. A paper suitable for publication in *Journal of Environmental Quality* will be prepared once all data management is completed.

SUMMARY OF PROCEDURES

Sites and Soil Descriptions

This field study was conducted during fall and spring seasons from fall 2002 to spring 2005 at 25 Iowa sites representing the soil series Clarion (Typic Hapludoll), Kenyon (Typic Hapludoll), and Tama (Typic Argiudoll). Over 580 simulated rainfall events were conducted on plots at these sites having histories of corn-soybean rotations, varied P application rates, and 2 to 10% slope. The sites had not received fertilizer or manure P at least during the previous six months. All sites had histories of chisel-plow and disk tillage, except for some sites managed with no-tillage that were included to evaluate runoff P relationships with manure application, crop residue type, and seasonal effects. Selected soil properties are shown in Table 1. Complementary work was conducted by scientists of the USDA/NRCS National Soil Survey Laboratory that included a complete physical and chemical characterization of the soil profile at one representative location for each soil series. The results of this basic soil characterization are not included in this report.

Rainfall Simulation Technique

The rainfall simulator and the simulation technique used were suggested by the National P Runoff Project. The simulator was built under the supervision of Dr. Brad Joern, following the same standardized specifications used for other simulators used nationwide. The basic structure was described by Humphry et al. (2002). A Veejet HH-SS50 WSQ nozzle (Spraying Systems, Wheaton, IL) supported by a cube frame made of aluminum pipes that measured 2.8 m on each side was placed 3 m above and at the center of the rained-on area. Although the rainfall fan covered an area approximately 7 m in diameter, preliminary calibrations using collector pans showed that this nozzle applied a uniform volume of water over an area approximately 5 m in diameter. Prior to applying manure treatments or simulated rainfall, galvanized metal borders were set into soil (to a 7.5 cm depth) encompassing a 1.5 m by 2 m area (referred to as a microplot hereafter) at the center of each field plot so that no wheel track traffic affected the study area. At the down-slope end of each microplot, and after applying manure and before applying rainfall, a flume was installed with the upper edge level with the soil surface. The flume was equipped with a canopy to exclude direct input of rainfall, and a 10-cm diameter plastic tube was used to route runoff water away from the microplot to a plastic collecting vessel placed outside of the rainfall area and buried so that its surface was just below ground level.

The day before conducting the standardized rainfall simulations, microplots were prewet by applying simulated rainfall until runoff began but without allowing runoff to occur. For the standardized simulation, rainfall was applied at 7.7 cm h^{-1} and runoff was collected *in toto* for 30 min. An additional 1-L sample was collected at the end of the 30 min period. The water was obtained from sources close to treatment plots for practical reasons. Water from rural water systems or well water was sampled each day and later analyzed for dissolved reactive P (DRP) by the ammonium-molybdate ascorbic-acid method (Murphy and Riley, 1962). The analyses showed that the water used never had more than 0.03 mg L^{-1} DRP and in most instances had less than 0.005 mg L^{-1} DRP. The bulk runoff sample was mixed thoroughly and a 1-L sample was collected. A sub-sample (20 to 30 mL) from each sampling period was filtered (0.45 µm) and acidified at the field for later analysis of DRP. Time to runoff, runoff volume, residue cover, and antecedent soil moisture were recorded. All runoff samples were kept in insulated boxes and were taken to a cold storage room (4 to 5 °C). Aliquots from the two 1-L runoff samples (30 min of runoff and after 30 min) were analyzed for bioavailable P with the Fe-oxide impregnated filter paper test (BAP), total P, and sediment. Procedures used for the BAP test were those described by Chardon (2000). Total P was determined with the alkaline-oxidation digestion procedure (Dick and Tabatabai, 1977) adapted to an aluminum digestion block (Cihacek and Lizotte, 1991).

Soil samples were collected from depths of 0-5 and 0-15 cm within the plot area (10 to 12 cores per sample) one or two days following simulated rainfall as suggested by the protocol. Samples were analyzed for Bray-P_1 (BP), Mehlich-3 P (M3P), Olsen P (OP), Fe-oxide impregnated filter paper P (FeP), water-extractable P (WP) and total P. Procedures for BP, M3P, and OP tests followed procedures recommended for the North-Central Region of the USA (Frank et al., 1998). Procedures used for FeP and total P tests were the same as those described above with appropriate modifications concerning sample handling. Procedures followed for WP were those described by Pote et al. (1996). The P in all soil and runoff extracts was measured using the Murphy and Riley (1962) colorimetric method.

SUMMARY RESULTS

Phosphorus Concentration in Surface Runoff

Runoff P concentrations ranged from 0.004 to 1.38 mg L^{-1} DRP and 0.016 to 4.1 mg L^{-1} BAP across the three soils. Mean runoff P concentrations were greater for BAP than for DRP, and were 3.2, 2.7, and 1.7 times greater for Clarion, Tama, and Kenyon soils, respectively. The differences between soils in the BAP-DRP ratio closely followed concentrations of sediment in runoff (not shown). Reasons for the differences cannot be explained with certainty by the soil property measurements available at this time. However, the close association with sediment loss suggests that differences might be explained by soil texture and structure differences between the soils.

Soil and Runoff P Relationships

Runoff DRP and BAP increased linearly with increasing soil P (Figs. 1 through 5). This result coincides with results observed in other states or research, although results for a few soils in other states have shown a curvilinear relationship with runoff P increasing faster at high soil P levels. Data for the Clarion soil in these five figures do not include results for a few soils at organic farms with a very long history of manure application and higher soil P level. No soil received manure or fertilizer P during the last 6 months, and these few soils had not received manure for at least one year, but these soils showed a relationship very different from all other soils and this is discussed in a following section. Correlations between runoff DRP or BAP and soil P for data shown in these figures were high for all soil P tests, and ranged from $r = 0.86$ to 0.96 across soils. Trends for P loads followed those presented for concentrations and are not shown. However, the strength of the relationships for P loads was much poorer than for runoff P concentrations. Runoff volume differences between locations of each soil series were very large and not consistent across soil series. The soil series was confirmed at each site and the same rainfall simulation protocol was followed at all locations. Therefore, large and inconsistent runoff volume variation within and across soil series suggests that differences in previous soil management at the sites, including the type of tillage done immediately before the simulations, did not achieve standardized hydrology conditions for these soils and precludes characterization of P loads. Large variation and inconsistencies were observed even when sites with corn or soybean crop residues were analyzed separately. However, this variation does not preclude a reliable characterization of relationships between soil P and runoff P concentration, mainly DRP, for the soil series.

The ranking of soils for DRP rates of increase with increasing soil P was consistent across soil P tests, although relative differences varied. For example, the slope of the relationship for Tama was slightly lower than for Clarion and Kenyon for the BP test (0.0015 vs. 0.0018 or 0.0017 mg DRP L^{-1} per mg P kg^{-1}) but was one-half for the OP test (0.0021 vs. 0.0039 and 0.0040 mg DRP L^{-1} per mg P kg^{-1}). The greatest differences were observed with OP and WP. The ranking of soils for BAP rates of increase with increasing soil P was similar to DRP but differences between soils and soil P tests were smaller. The strength of the relationships between BAP and soil P also was approximately similar to those for DRP.

Lower rates of runoff P concentration increase with increasing soil P for the Tama soil are consistent with a higher clay concentration (Table 1) that suggests a higher P sorption than for other soils. However, extractable Mehlich-3 Al and Fe or soil pH (Table 1) did not suggest clear P sorption differences between soils.

Soil Sampling Depth and Runoff P

A shallow soil sampling depth (0-5 cm) improved relationships between runoff P and soil P compared with a deeper (0-15 cm) depth for all soils (Fig. 6). However, the slopes of the relationships differed between sampling depths only for the Tama soil. Improved correlations with the shallower sampling depth for all soils, but differences in slopes only for the Tama soil, is explained by differences in soil P stratification (not shown). Soil P was more highly stratified in most Tama soil plots. The very poor relationship for the Kenyon soil using a 0-15 cm sampling depth mainly is explained by large P stratification at 12 plots (average M3P value of 530 mg P kg^{-1} for 0-5 cm and 77 mg P kg^{-1} for 0-15 cm). Omission of these atypical plots improved the relationship for this soil and depth to $r^2 = 0.49$.

Manure Application and Runoff P

Runoff DRP increased linearly with increasing soil P in soils with or without histories of manure application (Fig. 7). It is important to remember that these analyses assess effects of manure application histories but no site received manure at least until 6 months prior to the rainfall simulations. The manures used included liquid swine, poultry, dairy, and beef manures, although liquid swine manure predominated. Relationships for runoff BAP also showed linear increases with increasing soil P and are not shown. Usually there were no significant runoff P differences between manured and non-manured soils at similar soil P levels. In the few instances when differences occurred, DRP or BAP concentrations were lower for the manured soil than for the non-manured soil. Two important issues are noteworthy when interpreting these results. One is that the manured and non-manured Kenyon and Tama soils had different soil P levels (lower for manured soils, although this is not normally seen), so a direct comparison of relationships for manured and non-manured soils is risky. The other issue refers to a previous comment concerning data for the Clarion soil from a few soils at organic farms. The results for these few soils are shown in Fig. 7 but were not included in Figs. 1 through 5. Runoff P from these few soils, with soil P levels ranging from about 300 to 1600 mg Mehlich-3 P kg^{-1}, was much lower than for all other manured or non-manured soils and the slope of the regression line was much smaller. The same result was observed for all other soil P tests (not shown), so this was not a soil-test method problem. We cannot explain this result with certainty. Long-term organic management obviously changed some chemical and/or physical soil properties in a way that altered the runoff-soil P relationships (significantly less runoff P than expected according to the soil P levels). Trends for P loads (not reported) for all these manured and non-manured soils often were higher for the non-manured soils at a similar soil P levels because of slightly greater runoff for non-manured soils (24.1 kg for manured soils and 26.8 kg for non-manured soils on average across all sites). On average, manured soils also took longer to reach runoff than non manured soils (4.4 min versus 4.0 min), had higher volumetric antecedent moisture (29.6% versus 26.1%), and required less water to prewet the microplots (51.8 L versus 53.3 L).

Seasonal Effects and Runoff P

Runoff DRP (and BAP, not shown) increased linearly with increasing soil P when simulated rainfall was applied in spring or fall seasons (Fig. 8). However, DRP was consistently greater for the rainfall simulations conducted in fall than in spring at any given soil P level. It must be noted that simulations were never conducted on the same microplots and that the number of sites with fall or spring simulations were not the same across years or for the three soils. This result could partly be due to simulated rainfall flushing relatively higher levels of P in pools following plant necrosis and a shift in soil P equilibrium. However, other changes in the experimental conditions, such as those related to site hydrology could have been involved. The P loads (not shown) were not consistently different for fall or spring seasons because runoff volume differed greatly and on average was 1.4 times greater in spring than in fall (28.1 kg versus 20.3 kg, respectively) although P concentrations tended to be higher in the fall. On average, time to runoff (4.2 min) and volumetric antecedent moisture (28%) were similar for both seasons, although more water was needed to prewet microplots in fall compared with spring (56.3 L versus 50.3 L). These results suggest that for future coordinated projects, more emphasis should be placed on standardizing management and methodology factors that influence runoff volume in different times of the year.

Crop Residue Type and Runoff P

Runoff DRP (and BAP, not shown) increased linearly with increasing soil P regardless of crop residue type (Fig. 9). Differences in DRP or BAP were small and not consistent between corn and soybean residues. It is important to note that in this study the soils under corn residue had lower soil P than soils under soybean residue so caution is needed when interpreting the results. Other measurements were not consistently different between the two residue types. On average, plots with corn residue had 25.3 kg runoff, took 4.0 min to reach runoff, had volumetric antecedent moisture of 29.7%, and required 55.9 L to prewet the microplots. Plots with soybean residue averaged 24.8 kg runoff, took 4.4 min to reach runoff, had volumetric antecedent moisture of 27.5%, and required 49.9 L to prewet the microplots.

Other Factors Affecting Runoff P Relationships

Several other factors influencing runoff P were investigated after combining data from all simulations. Study of runoff P differences between samples collected *in toto* for the first 30 min of runoff and the sample collected immediately after 30 min indicated that the timing of sample collection influenced measured runoff P concentrations. The DRP, BAP, and total P concentrations in runoff decreased with time as simulated rainfall was continually applied. On average, DRP was 0.43 versus 0.35, BAP was 0.77 versus 0.68, and total P in runoff was 3.2 versus 2.7 mg L^{-1} for samples collected during the first 30 min of runoff and after 30 min, respectively. Total solids also decreased with runoff time, and on average was 3162 versus 2658 mg kg^{-1}. This latter result would indicate a decreasing P enrichment factor with increasing runoff time, and that initial runoff events pose a greater risk of particulate P loss. Total dissolved solids were measured only for the first 30 min of runoff, and on average were approximately 30% of the total solid concentration.

The influence of other factors on runoff P concentrations is shown in Table 2. These factors include residue cover, total solids, total dissolved solids, prewet water volume, soil antecedent moisture, time to runoff, runoff volume, an index of soil P saturation, total soil C, and field slope. Although most correlation coefficients were low, positive or negative relationships can be determined. For instance, negative relationships were apparent for relationships between runoff P concentrations (DRP, BAP, and TPR) and percent residue cover, soil antecedent moisture, and time to runoff. Positive relationships were evident for total solids, soil P saturation, and total C. It should be noted that although soil P saturation correlated well with runoff P concentrations ($r = 0.73$ for BAP for example), the routine agronomic soil P tests were just as good or better correlated ($r = 0.81$ for the relationship between BAP with Olsen P, for example).

Relationships between runoff volume, sediment, and other measurements are shown in Table 3. Correlation coefficients, although generally weak indicate runoff volume was inversely related to percent surface residue cover, prewet water volume, and time to runoff after simulated rainfall began. Total solids concentration was inversely related to percent surface residue cover and antecedent soil moisture, and positively related to runoff volume. The only other relationship worth mentioning is the weak positive relationships between surface residue cover and antecedent soil moisture and time to runoff.

CONCLUSIONS

Runoff P concentration from these typical Iowa soil series were highly and linearly correlated to soil P measured by five tests. Rates of runoff P increase with increasing soil P were lower for Tama than for Clarion or Kenyon soils, but the difference was affected by the soil P method used. The strength of relationships between runoff and soil P improved with a shallow soil sampling depth mainly in stratified soils but changes in slope of the relationships were not consistent across soils. Soils with a history of manure application showed similar or lower runoff P concentrations and had lower runoff volumes compared to non-manured soils. Measured runoff P concentrations were greater in fall than spring, but usually greater runoff volumes in spring than fall determined no consistent seasonal differences for P loads. Differences between soil under corn or soybean residue were not important factors for P concentration or runoff volumes. However, greater percent residue cover was an important factor reducing runoff P, sediment concentrations, and runoff volume. Overall, the study showed small differences in the relationship between soil P and runoff P between these soil series and that previous management and the soil-test P method used were more important at determining differences between soils.

PUBLICATIONS

A paper suitable for publication in *Journal of Environmental Quality* will be prepared once all data management is completed, so no scientific paper has been published in a peer-reviewed journal yet. However, partial results of the project have been shared at many meetings involving scientists, extension agronomists, and nutrient management planners. The following are abstracts or articles published or in press at this time.

Mallarino, A.P, and L. G. Bundy. In press. Agronomic and environmental implication of phosphorus management practices. In Gulf Hypoxia and Local Water Quality Concerns. A Workshop Assessing Tools to reduce Agricultural Nutrient Losses to Water resources in the Corn Belt. Proceedings. Sep. 26-28. Ames, IA.

Allen,B.L., A.P. Mallarino, and M.U. Haq. 2005. Relationship between soil and runoff phosphorus for three typical Iowa soils: a component of the national phosphorus runoff project. Agron. Abs. [CD-ROM]. ASA-CSSA-SSSA. Madison, WI.

Mallarino, A.P. 2005. Phosphorus - Impacts of fertilizer applications and management practices on the environment. In Illinois 2005 CCA Conference. [CD-ROM] Dec. 15. Springfield, IL.

Mallarino, A.P., B.L. Allen, and M.U. Haq. 2005. Manure management impacts on phosphorus loss with surface runoff and on-farm phosphorus index implementation. An overview of ongoing research. In Agriculture and the Environment Conf. Proceedings [CD-ROM]. March 8-9, 2005. Iowa State Univ. Extension, Ames, IA.

Mallarino, A.P., and K. Pecinovsky. 2005. Runoff phosphorus loss as affected by tillage, fertilizer, and swine manure phosphorus management in corn-soybean production systems. p. 46-47. In Annual progress reports-2004. Northeast research and demonstration farm. ISRF04-13. Iowa State Univ., Ames, IA.

Mallarino, A.P. 2004. On-farm implementation of the phosphorus index: Observed risk ratings and impacts on fertilizer and manure phosphorus management. p. 145-152. In The Integrated Crop Management Conf. Proceedings. Dec. 1-3, Ames, IA. Iowa State Univ. Extension.

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Pote, D.H., T.C. Daniel, D.J. Nichols, A.N. Sharpley, P.A. Moore, Jr., D.M. Miller, and D.R. Edwards. 1996. Relationship between phosphorus levels in three ultisols and phosphorus concentrations in runoff. J. Environ. Qual. 28:170-175.

Table 1. Selected average soil properties at a 0 to 5 cm sampling depth (relevant ranges are shown for the P soil tests).

Property	**Clarion**	**Kenyon**	**Tama**
Bray-P_1 (mg kg^{-1})	5-1220	16-705	8-865
Mehlich-3 P (mg kg^{-1})	5-1663	17-860	7-1012
Olsen P (mg kg^{-1})	2-359	8-282	4-654
Fe-oxide P (mg kg^{-1})	3-359	2-339	5-474
Water-extr. P (mg kg^{-1})	1-190	3-165	1-284
Mehich-3 Fe (mg kg^{-1})	210	186	159
Mehich-3 Al (mg kg^{-1})	719	691	790
Total C (g kg^{-1})	22	24	26
Clay (g kg^{-1})	184	219	288
pH	5.8	6.9	6.8

Table 2. Correlation between concentrations of dissolved reactive P (DRP), bioavailable P (BAP), and total P (TPR) in runoff as affected by selected site and soil properties.

Measurement	DRP	BAP	TPR
Residue cover	-0.12	-0.35	-0.47
Total solids	0.08	0.36	0.62
Total dissolved solids	-0.09	-0.13	-0.10
Prewet water volume	0.05	-0.03	-0.13
Soil antecedent moisture	-0.21	-0.31	-0.25
Time to runoff	-0.15	-0.24	-0.25
Runoff volume	0.04	0.15	0.27
Soil P saturation	0.52	0.73	0.69
Total soil C	0.17	0.25	0.22
Field slope	0.08	0.08	0.06

Table 3. Correlation matrix for various factors influencing surface runoff.

Measurement	Residue cover	Total solids	Prewet volume	Antecedent moisture	Time to runoff
Total solids	-0.38				
Prewet water volume	0.03	-0.08			
Antecedent moisture	0.32	-0.26	-0.03		
Time to runoff	0.27	-0.11	0.03	0.09	
Runoff volume	-0.43	0.26	-0.19	0.04	-0.28

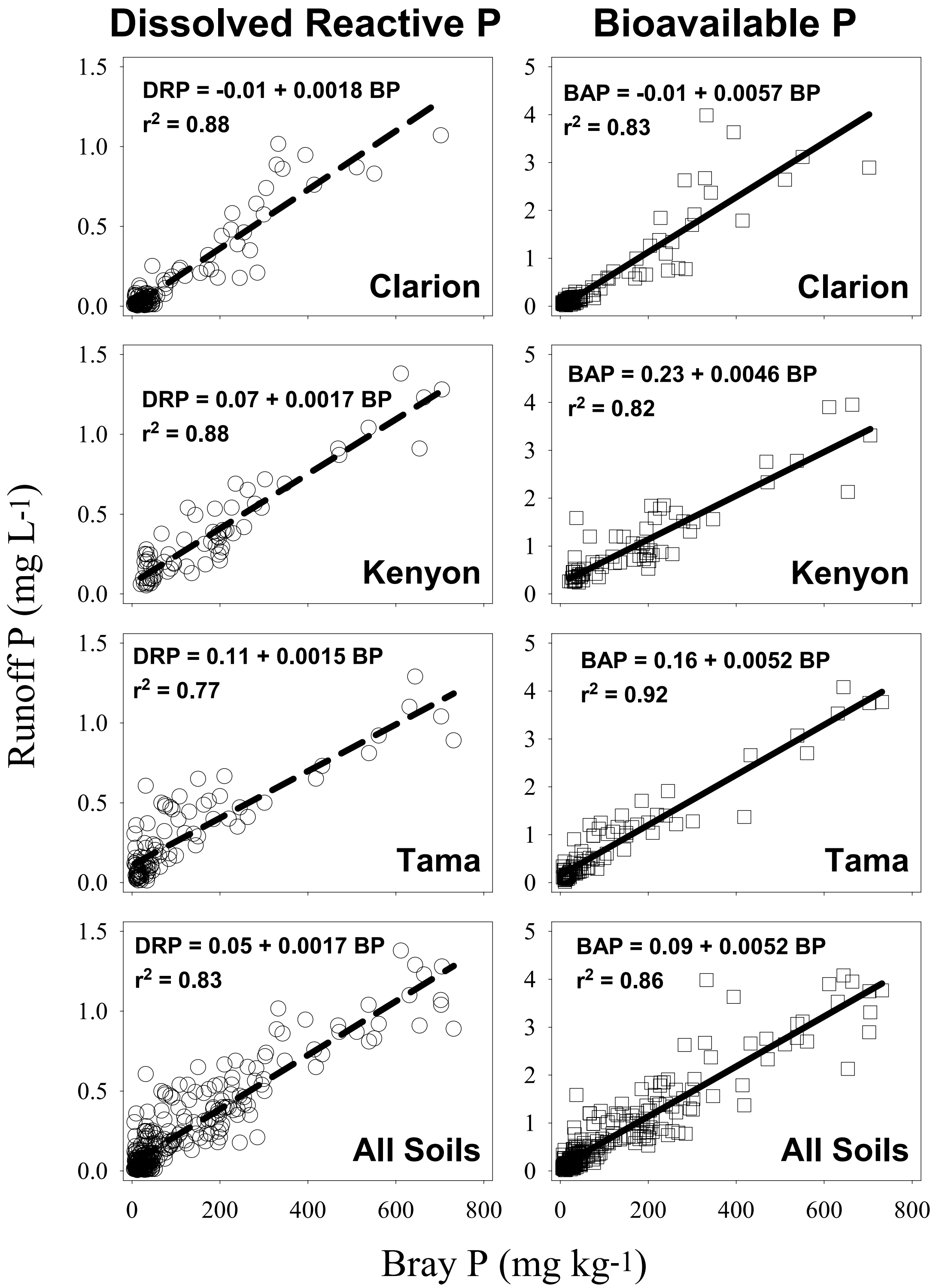

Fig. 1. Relationship between dissolved reactive P or bioavailable P in runoff and soil P measured with the Bray-1 test for three Iowa soil series.

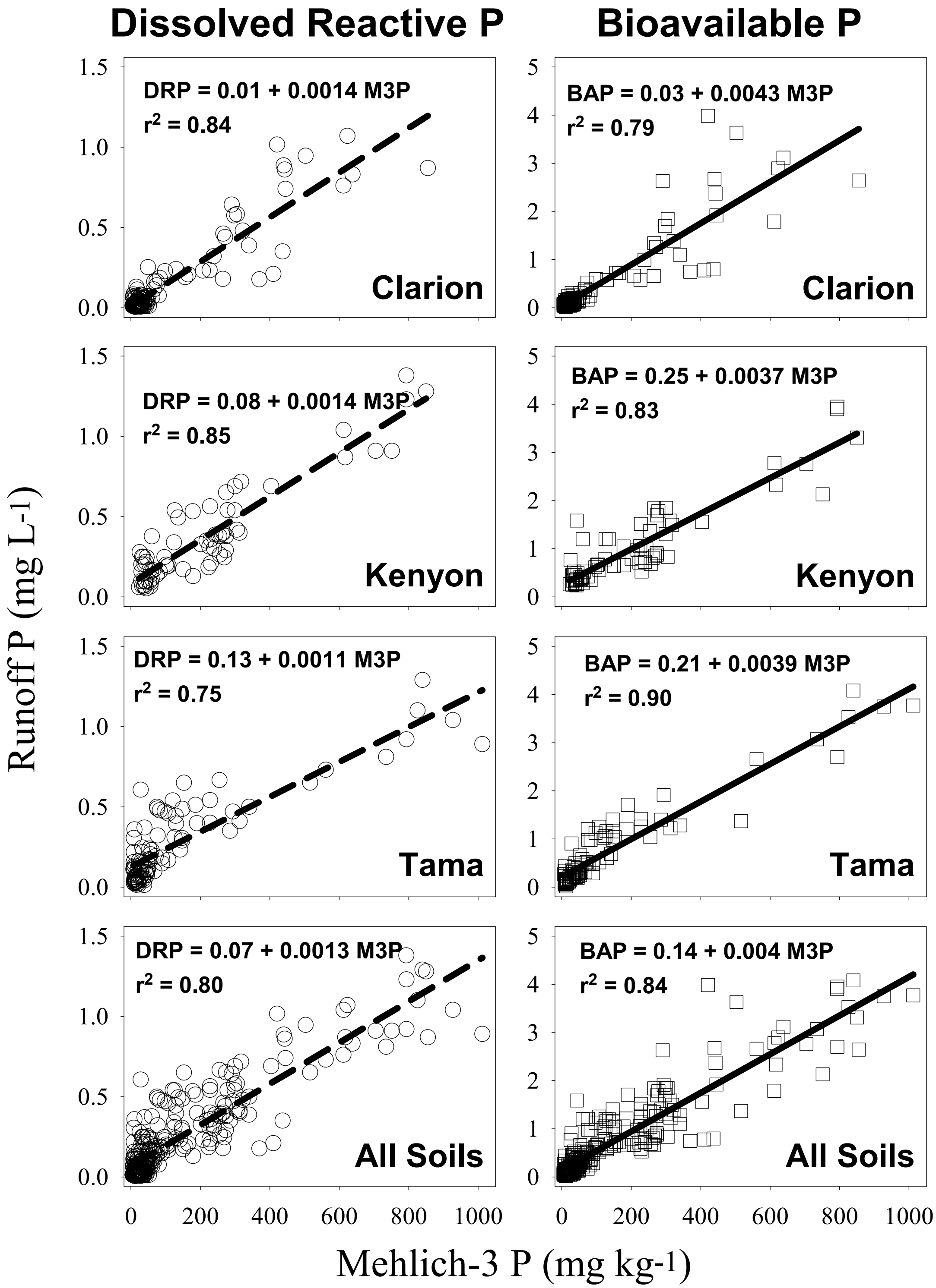

Fig. 2. Relationship between dissolved reactive P or bioavailable P in runoff and soil P measured with the Mehlich-3 test for three Iowa soil series.

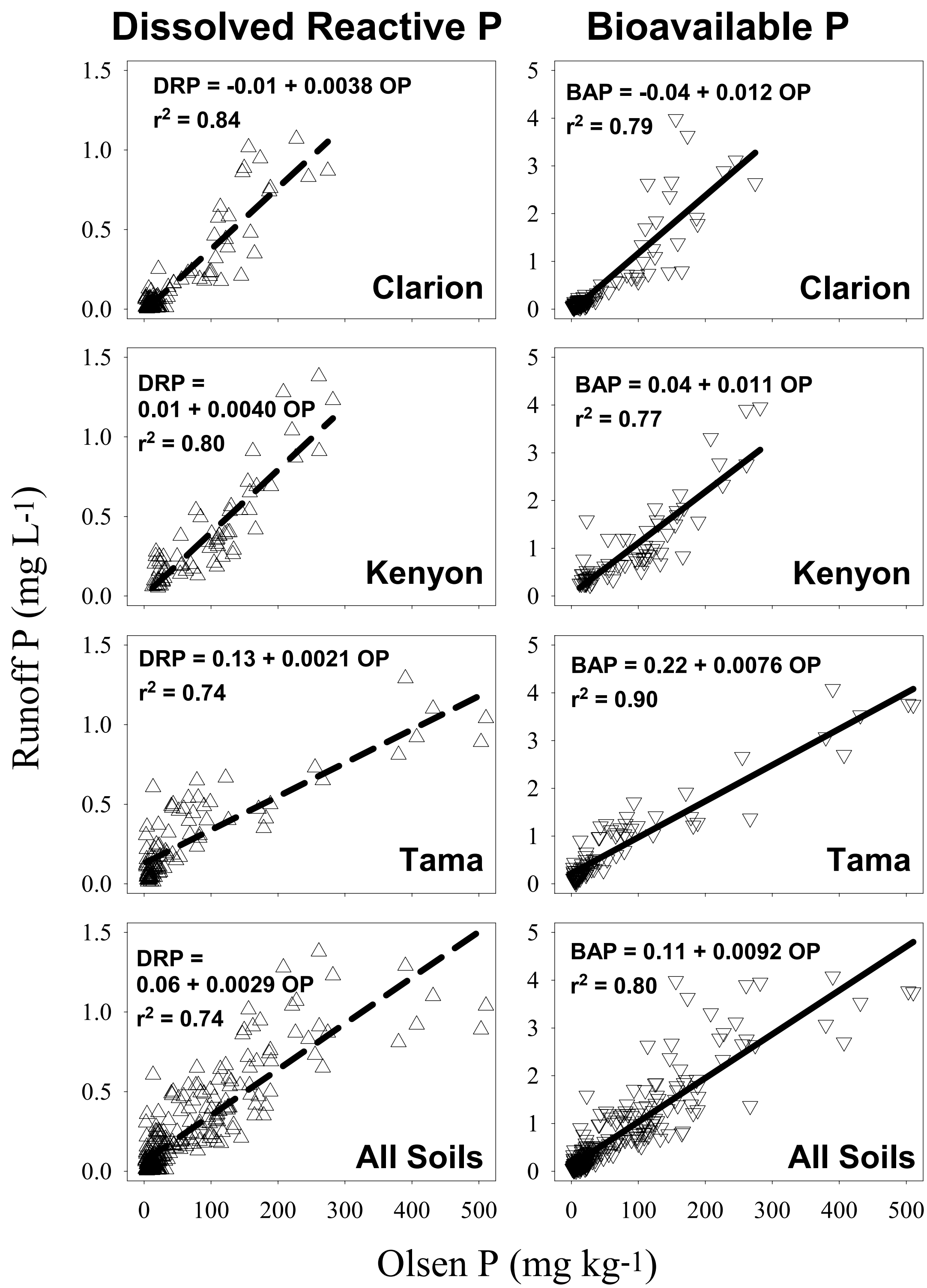

Fig. 3. Relationship between dissolved reactive P or bioavailable P in runoff and soil P measured with the Olsen test for three Iowa soil series.

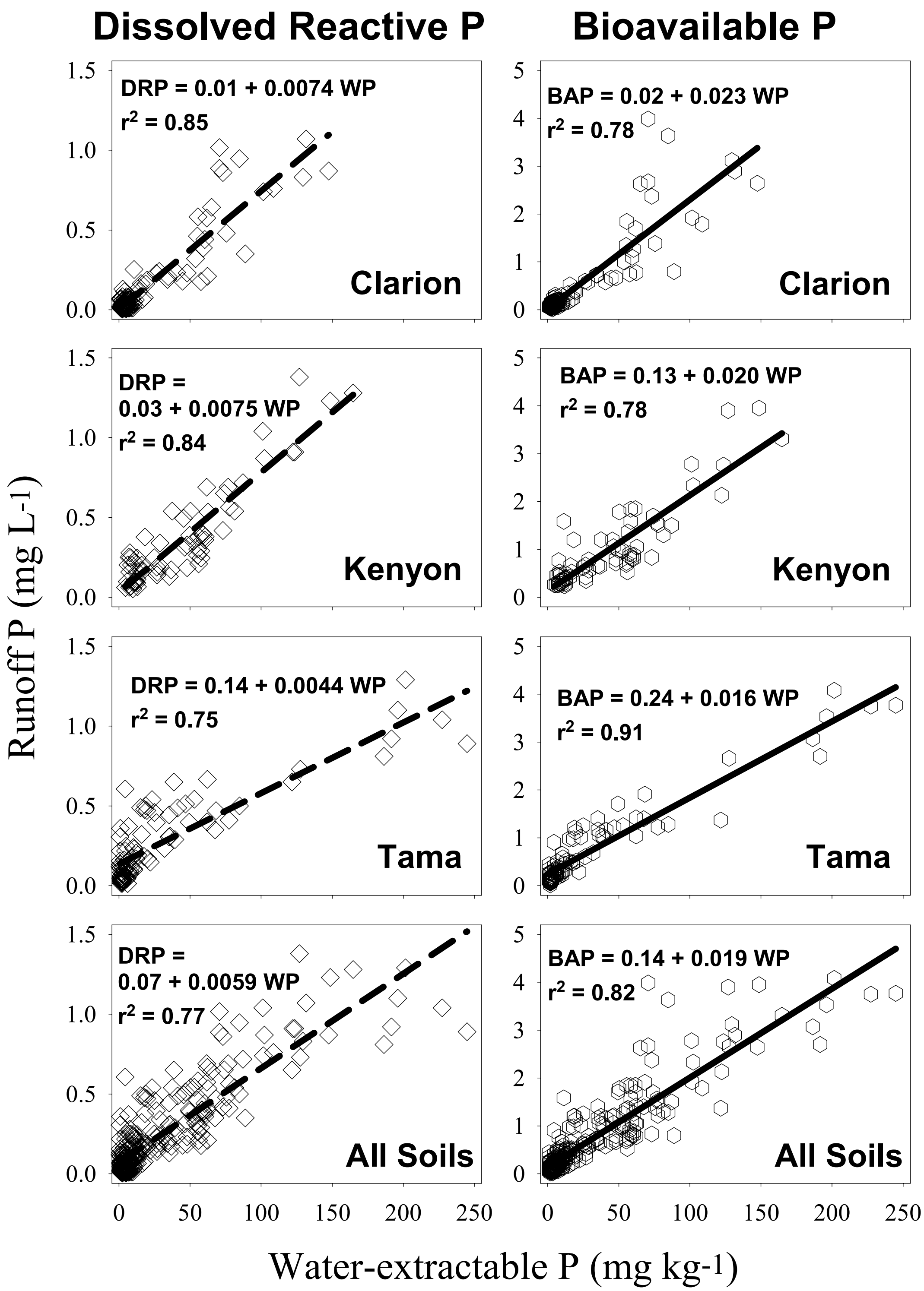

Fig. 4. Relationship between dissolved reactive or bioavailable runoff P and soil P (0-5 cm) measured with the water-extractable test for three Iowa soils.

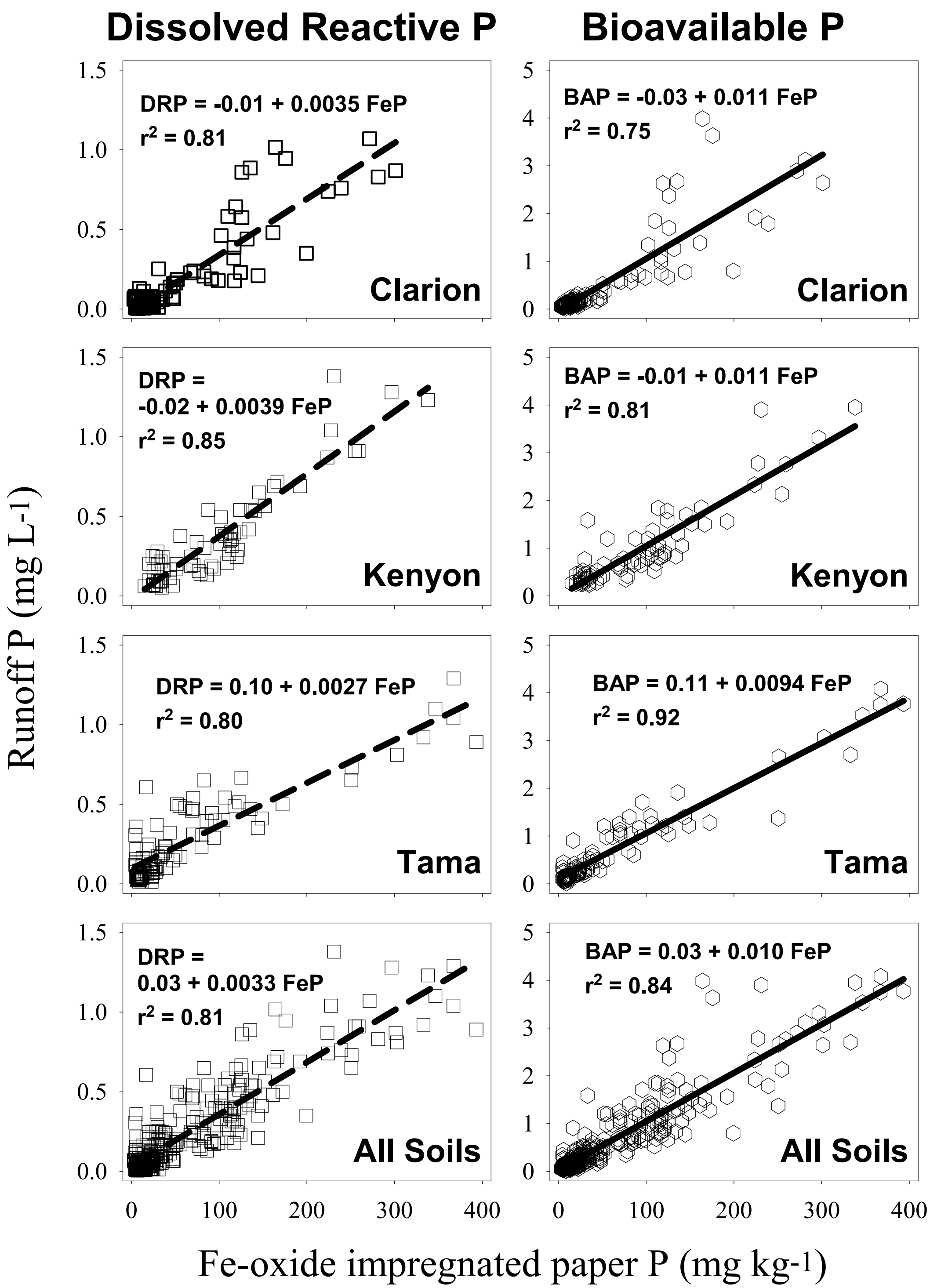

Fig. 5. Relationship between dissolved reactive P or bioavailable P in runoff and soil P (0-5 cm) measured with the Fe-oxide impregnated filter paper test for three Iowa soils.

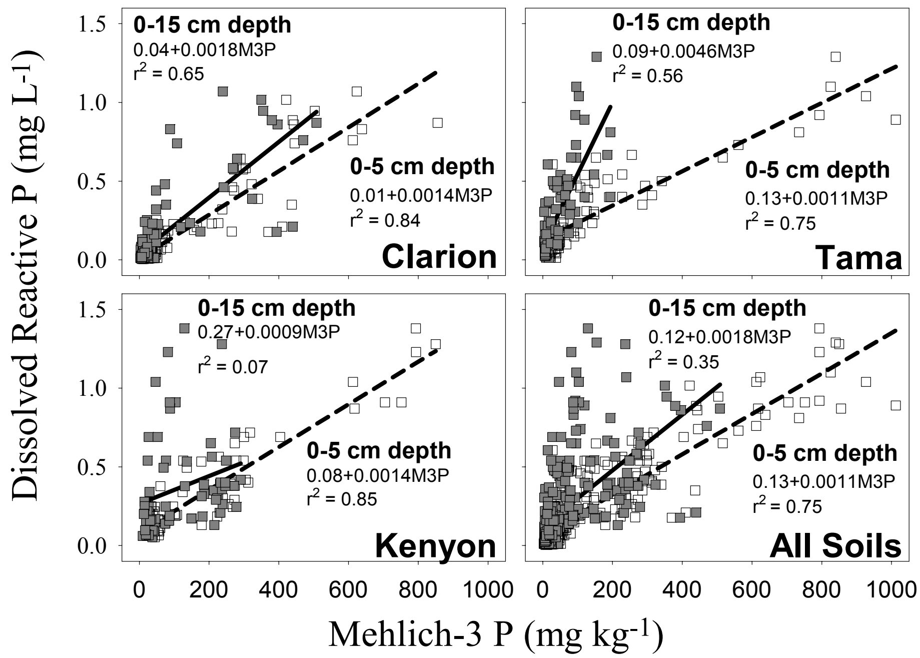

Fig. 6. Relationship between runoff P and soil-test P measured at 0-5 cm and 0-15 cm depths for three Iowa soils.

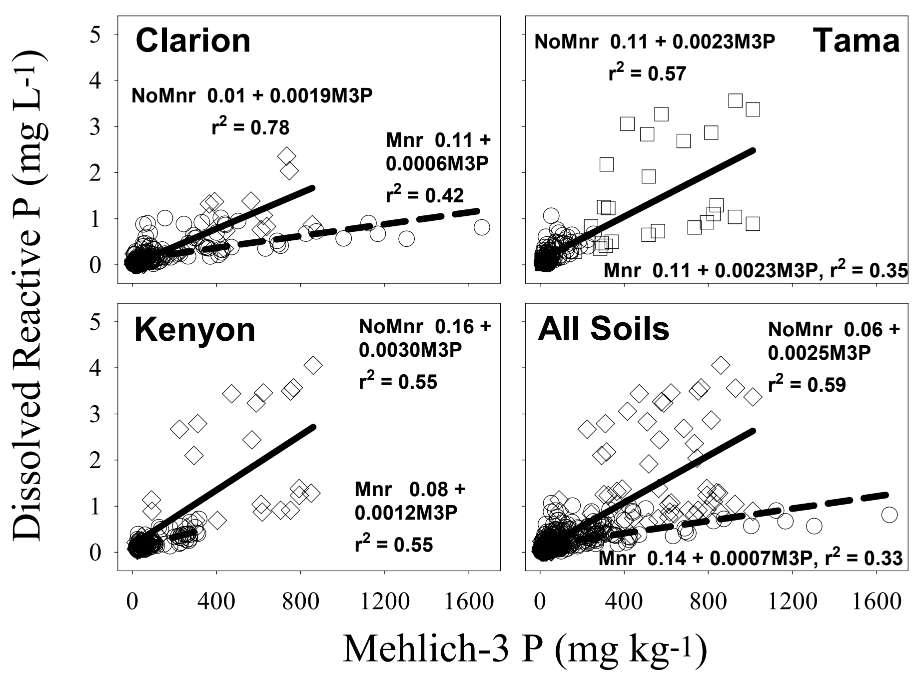

Fig. 7. Relationship between runoff P and soil-test P (0-5 cm depth) for three Iowa soils with histories of no manure (No Mnr) or manure application (Mnr). Regression lines for manured Kenyon and Tama soils are not seen clearly because soil P was <400 mg P kg^{-1}.

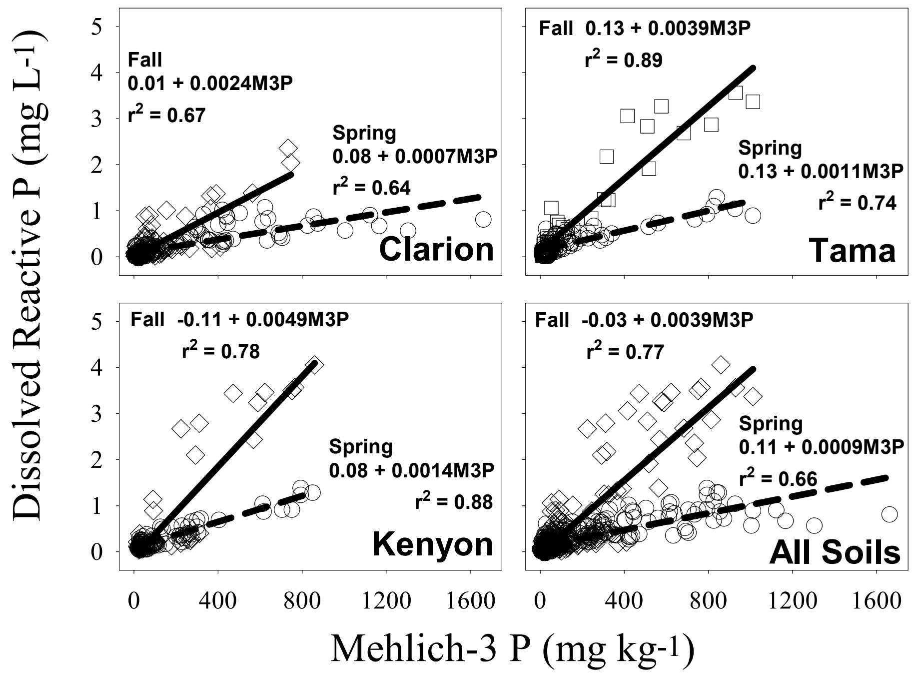

Fig. 8. Relationship between runoff P and soil-test P (M3P) measured at a 0-5 cm depth for rainfall simulations conducted in fall or spring for three Iowa soils.

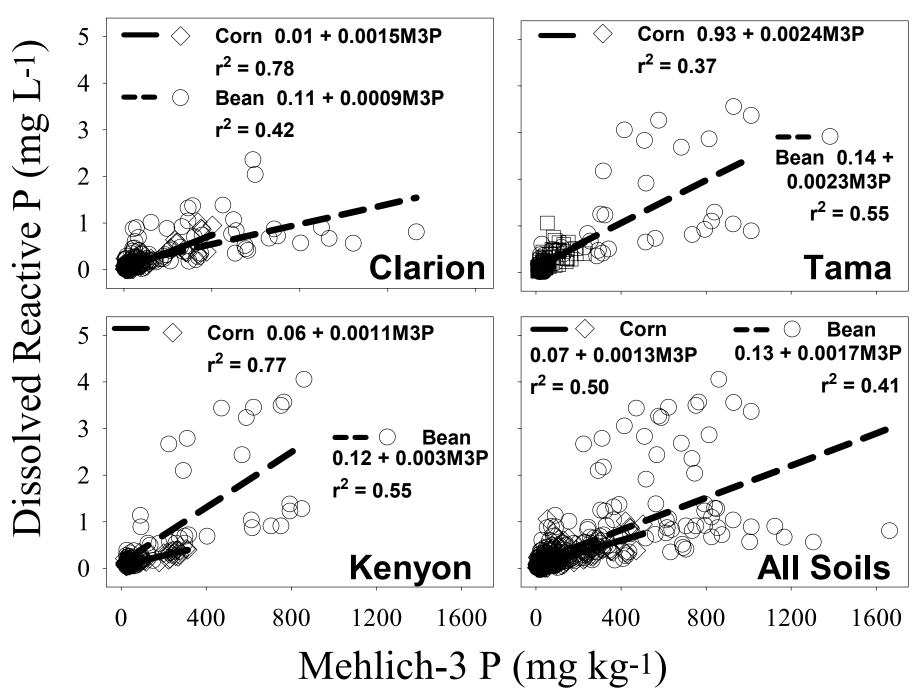

Fig. 9. Relationship between runoff P and soil-test P measured at a 0-5 cm depth for three Iowa soils with corn or soybean (Bean) residue. Regression lines for corn are not seen clearly because soil P was <500 mg P kg^{-1}.