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ABSTRACT
Phosphorus (P) in runoff from agricultural lands is an important contributor to surface water eutrophication. To quantify P losses from organic (poultry litter [PL]) and inorganic (triple superphosphate [TSP]) P amended soils, the relationship between runoff P and Olsen and Bray 1 soil test P (STP) in two geographic zones of Puerto Rico was evaluated, using simulated rainfall. The soils were an Ultisol-Oxisol complex with nativized pastures (*Paspalum Notatum*, *Cynodon dactilon* and *Digitaria eriantha*) in Mayagüez and an Ultisol with grass cover (*Brachiaria Decumbens*) in Corozal. The dissolved P fraction (DP) corresponded to 80% of total P (TP) concentrations in runoff in Mayagüez, while in Corozal, DP represented between 32 and 35% of TP concentrations in runoff in TSP and PL amended soils, respectively. Increase in slope and groundcover within and between sites reduced the DP/TP ratio in runoff. The TP and DP concentrations in runoff increased with STP, as modeled with a single exponential model. Organic residues in surface soil from amendment and plant material increased P mass losses and concentrations in PL amended soils. Runoff DP and TP concentrations were reduced with increases in runoff volume during the event and with antecedent soil moisture. Environmental critical STP levels in inorganic amended soils, calculated based on a 1 mg L^{-1} DP threshold in runoff were between 176 and 184 mg kg^{-1} for Olsen P. For Bray 1 STP, these thresholds were between 143 and 206. In PL amended soils threshold values were 88 and 111 mg kg^{-1} for Olsen and Bray 1, respectively.

INTRODUCTION

Continuous P additions in agriculturally intensive production areas, from organic and inorganic sources frequently exceed the agricultural and animal productivity outputs (Gburek and Sharpley, 1998). This condition has resulted in increases of P in soil which can be quantified by an agronomic soil test. With little or no residual surface soil-P, there is a positive quantitative relationship between STP and P concentrations in runoff (Pote et al. 1999a; Gaston et al. 2003; Hansen, et al., 2002). For example, Sharpley et al., (1996) describe that STP can predict between a 58 and 98% of the DP variation in runoff. Surface water bodies that are long-term receptors of runoff from areas with high STP are commonly associated with accelerated eutrophication.

The principal P soil inputs are fertilizers, manures, crop residues, atmospheric deposition and land-applied industrial or municipal wastes. Soil P losses are associated with eroded sediments, leaching, runoff and crop uptake. Loss of P attached to sediments is significant when P transport is due to erosion processes. Once sediment losses from agricultural lands are minimized, the single most important negative process that impacts water quality is P in runoff, because lateral subsurface flow from watertable interflow is of lesser importance (McDowell and Sharpley, 2001; Sharpley et al., 1994; Simard et al. 2000). The most important soil factors that influence the concentration of P in runoff are the concentration of P in soil, the level of interaction between soil and applied P, the location of P in the soil profile (Baker and Laflen, 1983). Hydrologic factors such as rainfall intensity and duration strongly affect P concentrations in runoff (Sharpley, 1985; Edwards and Daniels, 1993). This effect is attributed to rain drop impact energy which causes dispersion and dispersion of soil particles, P sorption/desorption in the sediment surface-aqueous interface and subsequent dilution by rainfall.

Field research conducted with naturally occurring rainfall and simulated rainfall, have found strong relationships between P in runoff and P in soil as quantified with varying STP methodologies such as Bray 1, Olsen and Mehlich 3 (Pote et al., 1996b; Aase et al., 2001; Sharpley et al., 2001; McDowell and Sharpley, 2001; Fang et al., 2002; Kleinman et al., 2002; Daverde et al., 2003; Andraski and Bundy, 2003; Gaston et al., 2003). This database has suggested that soil testing can be used as a tool for the sustainable management of P in agricultural soils. A critical STP level in combination with other site vulnerability factors can be used to guide P applications to soils with varying physico-chemical characteristics and cropping practices.

The STP-runoff P relationships can be influenced by physical properties, mineralogy and chemical properties (Bhatti et al. 1998; Burt et al., 2002; Schroeder et al., 2004). This may be a reason why both linear and curvilinear relationships between STP and P in runoff have been found (Sharpley et al., 2001; Guidry et al., 2004). The slope of the linear regression between STP and DP concentration, termed the soil P extraction coefficient, varies due to soil properties such as clay content (Cox and Hendricks, 2000), P sorption capacity (Sharpley, 1995), $CaCO_3$ content (Torbert et al., 2002 and Fang et al., 2002), hydrologic response variability (Pote et al., 1999a; Andraski and Bundy, 2003 and Sharpley and Kleinman, 2003), antecedent soil moisture (Pote et al., 1999b and Sharpley and Kleinman, 2003). Other external factors such as soil management practices and crop production systems also influence this extraction coefficient (Sharpley et al., 2002, Tarkalson and Mikkelsen, 2004). The patterns of P in runoff from fields where P has recently been surface-applied are different than those where P has reacted and formed part of the soil matrix (Kuykendall et al. 1999; Kimmel et al. 2001) because transport in the former is due to detachment from residual material on surface soil, which need not necessarily be quantified by a soil test.

Some agricultural soils of the island of Puerto Rico have elevated STP levels and are characterized by highly favorable runoff transport conditions (Martínez et al., 2002). In addition, surface water bodies have been ranked in the mesotrophic status and agricultural activities may be partly responsible. These characteristics may be shared by other areas of the tropics and subtropics, yet few field studies have been conducted that evaluate P losses from highly weathered soils such as Ultisols and Oxisols (Pote et al. 1999a, 1999b, Cox and Hendricks, 2000; Sharpley and Kleinman, 2003; Schroeder et al., 2004) found in tropical and subtropical areas. Sotomayor-Ramírez et al. (2004) suggested environmental STP categories for tropical soils using Olsen, Bray 1 and Mehlich 3 soil tests. Low and high limits of critical STP values were based on 0.5 and 1 mg L^{-1} DP concentration in runoff. The results presented in this manuscript address preliminary findings reported by Sotomayor-Ramírez et al. (2004) with the objective of describing the soil and hydrologic factors that influence concentrations of P in runoff, and validating suggested environmental critical STP levels.

MATERIALS AND METHODS

Field experiments were conducted within a 2.5 ha field in Alzamora University Farm in Mayagüez (site 1) and in twenty plots within fields in the University Agricultural Experimental Station in Corozal (site 2), Puerto Rico. The soil in Alzamora was an Ultisol-Oxisol complex, consisting of greater portions of Humatas (Very-fine, parasequic, isohyperthermic Typic Haplohumults) and Consumo (Fine, mixed, semiactive, isohyperthermic Typic Haplohumults) series, and lesser portions of Daguey series (Very-fine, kaolinitic isohyperthermic Inceptic Hapludox) (Beinroth et al., 2003). The field site had groundcover of 80 to 95% of Bahia (*Paspalum notatum*), Bermuda (*Cynodon dactilon*) and Pangola (*Digitaria eriantha*) species, with slopes that ranged from 5 to 20%. The mean clay content was 50%, mean lime content was 28% and soil organic matter content (OM) was from 2.3 to 6.5 (Table 1). In Corozal, soil was an Ultisol corresponding to Humatas series (Very-fine, parasequic, isohyperthermic Typic Haplohumults) (Beinroth et al., 2003). The plots had groundcover of Brachiaria (*Brachiaria decumbens*) that ranged from 43 to 93% and slopes that ranged from 15 to 27%. The mean soil clay content was 42%, mean lime content was 25% and OM ranged from 4.2 to 6.5 (Table 1). The OM values were obtained after P amendment in both sites.

In Alzamora, soils were sampled (0 to 10 cm) on a grid of 2.74 m × 2.74 m to assess the Olsen STP status. Four subsamples within the center area of each plot were collected. In April and August 2003, plots with STP less than 150 mg kg^{-1}, were amended with triple super phosphate (TSP) for obtain STP levels up to 250 mg kg^{-1}. In Corozal, nine plots of 407 m^2 each were amended with 25, 50, 100, 150, 300, 450, 600, 900 and 1200 kg P ha^{-1} of TSP; another eight fields were amended with 25, 50, 150, 300, 450, 600, 900 and 1200 kg P ha^{-1} of poultry manure (PL). The organic amendment was divided in two applications (October 2003 and the other in February 2004) and the inorganic amendment was divided in four applications (October and December 2003 and February and May 2004). Amended fields remained at least 5 to 6 months under natural growth conditions.

The sampling plot layout scheme and rainfall simulations were developed according to the National Phosphorus Research Project (NPRP) for Simulated Rainfall – Surface Runoff Studies Protocol (USDA – NRCS, 2001). Rainfall was performed on paired plots which were split to form subplots, where each was an experimental unit. The subplot area was 1m wide × 2m long, with the long axis orientated down the slope. Metal borders were installed 10- and 5-cm above and below ground level, respectively. Runoff was diverted to a collector placed at the bottom of each subplot. Before the rainfall simulation, grass height was cut evenly to a height of 8 cm throughout the plot. Soil slope, groundcover (transect method) and volumetric soil moisture content using Theta probe (Dynamax Inc.,TX) were quantified.

A rainfall intensity of 70 mm hr^{-1} for 30 minutes after runoff initiation was applied to each plot. This value corresponds to the maximum rainfall intensity occurring in 1 hour for 10 yr return period in both study areas (Junta de Planificación de Puerto Rico, 1975). For rainfall simulations a TLALOC 3000 rainfall simulator (Joern's Inc., West Lafayette, IN) and a FullJet ½HHSS50WSQ nozzle (Spraying Systems Co., Wheaton, IL) were used. The nozzle was located at 3.05 m above the ground to achieve terminal velocity in rain drops. Previous calibrations were developed to determine the flow pressure-rainfall intensity relationship and to asses the rainfall uniformity within each plot.

The rainfall scheme consisted of two rainfall simulations at 24 h intervals at each plot. The time interval affected the soil moisture conditions, presenting soil moisture content values lower than field capacity in the first simulation to values at or near field capacity in second simulation. After each of the rainfall simulation was initiated, time to runoff was registered. Runoff was quantified gravimetrically at 1 min intervals during 30 min to obtain the runoff hydrograph for each subplot. At 10, 20 and 30 min after runoff initiated, a 500 ml subsample of the cumulative runoff was obtained to determine the suspended sediment (SS), total P (TP) and dissolved P (DP) concentrations. A source water sample was obtained prior to each simulation to determine TP, DP and SS concentrations, which resulted in average values of 0.14 mg L^{-1}, 0.12 mg L^{-1} and 0.002 g L^{-1}, respectively and an average pH value of 7.02. To eliminate P variability in data analysis, DP, TP and SS water source concentrations were subtracted from the respective runoff values.

Soil samples were quantified for extractable P using the Olsen method (Sims, 2000a) and Bray 1 method (Sims, 2000b). Soil pH was measured using a 1:1 (soil:water) proportion. Soil texture was quantified using the Bouyucuos method (Montenegro and Malagón, 1990) and organic matter concentrations were quantified using Walkey and Black procedure (Nelson and Sommers, 1982). Runoff DP concentrations were quantified colorimetrically (Murphy and Riley, 1962) after filtering through a 0.45 µm pore diameter membrane. Runoff TP concentrations were quantified colorimetrically after digesting with potassium persulphate as described by Pote and Daniel (2000).

Statistical Methods
A total of eighty two rainfall simulations were conducted; fifty in Alzamora and thirty-two in Corozal. Olsen and Bray 1 STP, slope, groundcover, soil moisture, OM and texture values quantified in each subplot were compared with a paired t-student test ($P<0.05$), to assess plot homogeneity. The same procedure was applied to the runoff depth (R), TP, DP and SS

concentrations in runoff to determine a possible rainfall uniformity incidence on subplot variability. Homogeneity and normality tests were evaluated for each parameter before undertaking correlation and analysis of variance (ANOVA).

To evaluate the change in soil properties (OM, pH and texture) due to the final STP level obtained, the plots were grouped by Olsen and Bray 1 soil P loss susceptibility categorical levels according to Sotomayor et al. (2004). The effect of P amendment source effect on soil properties within and among susceptibility levels was evaluated using ANOVA. Means separation was performed using Tukey's Least Significant Difference (LSD) test (P<0.05).

The effects of P source amendment and site (inorganic site 1, inorganic site 2 and organic site 2), STP categorical grouping (five levels), and day of simulation (day 1 and day 2) on DP, TP and SS concentrations and mass losses within each site and between sites was performed. When the effects were significant, groups and level means where separated using Tukey's LSD test (P<0.05). Simulation day and P amendment source effects on initial flow time, soil moisture, runoff depth (R), average flow in 30 min (Q), total precipitation (P) and R/P ratio were evaluated using the same statistical procedures.

Olsen and Bray 1 STP were correlated with TP and DP runoff concentrations. The best regression model (model with greater R^2 and smaller standard error values) was determined in each interval runoff time (10, 20, 30 minutes), each simulation day, each P amendment source and each site. Critical STP levels to achieve 1 mg L^{-1} DP were quantified from the non-linear regression models. The double interaction effects of OM and STP, and antecedent moisture content and STP on DP and TP runoff concentrations were evaluated using ANOVA procedures. If effects were significant a multiple regression model was determined.

Statistical differences (ANOVA) and mean differences were determined using INFOSTAT 2.0 software (Universidad de Córdoba, Argentina). Best model and correlation variables were obtained using CurveExpert 1.3 (Microsoft Corporation, USA) and SigmaPlot 6.1 (SPSS, USA) software. Correlation coefficient (R^2) and significance test (P<0.05) for each variable were determined in each regression.

RESULTS AND DISCUSSION

Amendment effects on soil properties

Addition of TSP and PL to soils increased initial STP values which were then classified into five categorical levels for each soil test (Low, Medium, High, Very High, Extremely High). Olsen and Bray 1 STP levels ranged from 6.9 to 352 mg kg^{-1} and from 2.8 to 337 mg kg^{-1} in Alzamora, respectively. In Corozal, Olsen and Bray 1 STP ranged from 0.01 to 245 mg kg^{-1} and from 0.01 to 350 mg kg^{-1}, for PL and TSP amended plots, respectively. At both sites an increase in OM levels were observed with increases in STP categorical levels probably due to greater biomass growth as a result of P addition (Table 1). In Alzamora, soil pH was significantly influenced by the STP level which changed due to TSP addition. A maximum pH value of 8.05 was attained at STP (Olsen) of 110 mg kg^{-1}, after which pH values decreased. We hypothesize that the addition of H_2PO_4 with TSP application will favor H^+ consumption thus increasing pH, according to:
$H_2PO_4 + H^+ + Fe(OH)_3 \leftrightarrow FePO_4 \cdot 2H_2O + H_2O$

When sufficient Ca occurs in solution, the excess orthophosphate will react with Ca to precipitates as Ca-phosphates favoring a pH decrease, according to:

$Ca^{2+} + H_2PO_4 + H_2O \leftrightarrow CaHPO_4{\cdot}2H_2O + H^+$

Within each STP category soil pH increased more with PL addition than with TSP addition (Table 1). Iyamuremye et al. (1996) reported an increase in soil pH with STP. The effect of organic amendments on pH may be attributed to a reduction of Al in solution and thus active acidity by Al complexation with organic ligands and organic C sorption to cation exchange sites (Hargrove and Thomas, 1981).

Hydrologic characteristics

The mean volumetric soil moisture content increased from day 1 to day 2 (32.3% to 39.5%) in Alzamora ($P<0.05$), and ranged from 36.4 to 40.4%, in Corozal. The initial time to runoff was always lower in day 2, but was not statistically significant in Corozal (Table 2). A decreasing curvilinear relationship was observed between soil moisture and time to runoff (Figure 1a), with faster runoff response in soils with greater antecedent soil moisture. At both sites, the runoff-precipitation depth ratio (R/P) (Figure 1b), runoff depth (R) and average flow (Q) parameters increased with soil moisture values and day of simulation, but a statistical difference was only observed in Alzamora. The lack of day of simulation effect observed in Corozal with regards to the hydrologic parameters may be due to the greater organic matter content and hence water retention capacity in the soil at Corozal and because there was a greater range of days in which precipitation did not occur which permitted lower soil moisture contents in the first day of simulation at Alzamora. Daily differences and greater uniformity in antecedent soil moisture and time to runoff in day 2 of simulation was reported by Sharpley and Kleinman (2003) and Hively et al. (2005), which attributed this condition to increased soil water content approximating saturation.

Relationship between STP and P runoff concentrations

In Alzamora, TP and DP concentrations in runoff were significantly influenced by day of simulation, which in turn was affected by the soil moisture content prior to simulation (Table 3). A similar condition was described by Sharpley and Kleinman (2003) attributing the decreasing DP concentration with moisture to a temporary dilution of the released P to runoff from the surface soil. Overall, mean TP concentrations in runoff ranged from 0.31 to 2.06 in day 1 and from 0.24 to 1.81 in day 2. Mean DP concentrations ranged from 0.31 to 1.73 mg L^{-1} in day 1 and from 0.30 to 1.12 mg L^{-1} in day 2, respectively.

In Corozal, TP and DP concentrations were not influenced by day of simulation. The range in TP concentrations was between 0.22 to 5.90 mg L^{-1} and from 0.16 to 9.92 mg L^{-1} for TSP and PL amended plots, respectively. The range in DP concentrations was between 0.08 to 3.98 mg L^{-1} and from 0.08 to 4.03 mg L^{-1} for TSP and PL amended plots, respectively. Where sufficient data was available for the High, Very High and Extremely High categorical levels, DP and TP concentrations were always higher in PL than in TSP amended plots evidencing a P amendment source effect.

Mean TP and DP concentrations in runoff increased with an increase in STP categorical levels using the Olsen and Bray 1 methods. Similar patterns were reported in other studies (Pote et al., 1996; Pote et al., 1999a; Andraski and Bundy, 2003; Andraski et al., 2003; Daverde et al., 2003;

Fang et al., 2003). A curvilinear exponential correlation consistent with that observed by Sharpley et al. (2001) and Guidry et al. (2004) was obtained in both sites for Olsen and Bray 1 STP methods (Figure 2). Regression parameters and R^2 values are presented in Table 4.

Lower regression coefficients were observed for PL amended plots. Andraski et al. (2003) reported lower regression coefficient values in STP-P concentration in runoff relationships in recently manured fields (less than 6 months) as compared with non-recently manured fields and suggest that recent manure additions tend to mask STP effects on P in runoff due to soluble P losses from manure. In Alzamora, the lower regression coefficient values in day 2 as compared to day 1 may have occurred due to a P dilution effect with an increase in runoff depth. Andraski et al. (2003) described that the regression coefficients for STP-P concentration in runoff relationship decreased as the more sediment and particulate P increased in proportion to TP concentrations.

The intercept of the regressions always were positive and describe DP and TP values when STP is zero. TP concentrations were 0.23 and 0.41 mg L^{-1} when very low P (< 4 mg kg^{-1}) was extracted using both Olsen and Bray 1 methods in Alzamora and Corozal. The positive regression intercept suggests that there is a P source that is not accounted for by quantification of P by means of a soil test (Schroeder et al., 2004). Organic residues, in the form of residual living and dead grass material, overlying the soil surface may be a potential source of P in runoff water. Sharpley (1981) reported that between 18 and 94% of P in runoff from bare soil was originated by P leached from the plant canopy. Timmons et al. (1970) reported P losses from grass residue of up to 0.3 kg ha^{-1}.

The DP/TP ratio was lower in Corozal than in Alzamora (Figure 3A). The soil moisture content was also an important factor diminishing the proportion of TP occurring in dissolved form at both sites, but was significant only in Alzamora where soils were drier in the first day of simulation than in Corozal (Figure 3B). This is confirmed by the lower DP-STP than TP-STP regression intercepts in both sites (data not shown). The greater SS concentrations in runoff in Corozal probably lowered the proportion of TP occurring in dissolved form. In Alzamora, the TP-STP and DP-STP regression intercepts were greater in day 1 than in day 2; in Corozal a similar non-significant trend was observed. This may have occurred because of washout of residual surface vegetative material in day 1, leaving less potential material for transport in day 2.

The DP fraction was 74, 56, and 40 % of the TP fraction in Alzamora, Corozal amended with inorganic P and Corozal amended with organic P, respectively. The DP/TP concentration ratio in runoff increased with increased groundcover and decreased slope (Figure 4). The DP/TP runoff concentration ratio was higher in day 1 in Alzamora, and was not affected by P amendment source and simulation day in Corozal. The observed decrease in the DP/TP ratio in runoff in Alzamora in the second simulation day (mean = 72%) was probably due to increased antecedent soil moisture, runoff depth, SS and PP concentrations. Pote et al. (1999b) and Sharpley and Kleinman (2003) showed that P concentration in soil water were lower in wet soils than in dry soils that received rainfall. A dilution effect due to greater runoff depth also favored low P concentrations in runoff from wet soils. However Pote et al. (1999a) described those other effects furthermore to dilution generates low P concentrations in runoff on high antecedent soil moisture conditions, when other effects are controlled. In Alzamora, P readsorption to suspended soil particles probably was limited due to the low SS discharge (generated by a high groundcover and a lower slope) which favored a high DP/TP ratio. McDowell and Sharpley (2002) and Sharpley and Kleinman (2003) described that a lower sediment discharge probably resulted in a lower readsorption of P by particles during the runoff event.

In areas where soil pH increased (Alzamora and Corozal amended with organic P), the regression intercept values were lower and regression increment values (soil P extraction coefficient) were greater when the Olsen P extraction method was used. The lower P extraction capacity of the Bray 1 method may be that soil pH and calcium increased with TSP application in Alzamora, and poultry manure application in Corozal. The acidity of the Bray 1 solution may have been partly neutralized due to the alkalinity in the amendments, and the formation of CaF_2 which decreased the solubilization of Fe-Al phosphates, and thus decreasing solution P. Fang et al. (2002) observed a similar condition in calcareous soils using different STP methods and was not able to obtain a close-fitting relationship between DP and Bray 1 STP.

The OM content significantly positively influenced DP and TP concentrations in runoff contributed by a given STP level (Figure 5A). Good et al. (2004) observed a similar effect of OM on STP-TP relationships. In contrast, an increase in soil moisture content reduced the DP concentration contributed by a given STP level (Figure 5B). The concentration of TP and DP in runoff tended to decrease with runoff depth as measured by runoff duration for both Olsen and Bray 1 P extraction methods (Figure 6) at both sites. However, when data were grouped according to P loss categorical levels the decrease in P concentration with runoff depth was most dramatic only in the Extremely High and High STP categorical levels in Alzamora (Figure 7). In Corozal, the trend was observed in both inorganic and organic P amended plots.

Both sites exhibited greater SS, TP and DP concentrations and mass losses during the first 10 min of runoff time. The DP dilution rates (DP reduction due runoff time increase in an event) were greater in Corozal than in Alzamora. In Corozal, DP dilution rates were greater in PL amended plots (from 0.003 to 0.07 mg L^{-1} min^{-1}) than in TSP amended plots (from 0.011 to 0.054 mg L^{-1} min^{-1}). In Alzamora, DP dilution rates were greater in day 1 (ranged of 0.006 to 0.027 mg L^{-1} min^{-1}) than in day 2 (range of 0.004 to 0.020 mg L^{-1} min^{-1}).

The TP and DP mass losses increased with STP categorical levels in Alzamora. In Corozal the effect of STP on DP and TP mass losses was apparent only in the Very High and Extremely High levels. Greater TP and DP mass losses were observed due to PL addition (Table 6).

Soil P extraction coefficient and environmental critical level

The soil P extraction coefficient corresponds to the slope of the linearized form of the STP-DP in runoff relationship. The value of this parameter was higher in PL amended plots than in TSP amended plots in Corozal. In PL amended plots, extraction coefficients were 0.01745 and 0.01265 mg DP L^{-1} mg^{-1} P kg for Olsen and Bray 1, respectively. Plots amended with TSP had P extraction coefficients of 0.0081 and 0.0069 mg DP L^{-1} mg^{-1} P kg for Olsen and Bray 1, respectively. In Alzamora for the first day of simulation, values were 0.0056 and 0.0062 mg DP L^{-1} mg^{-1} P kg for Olsen and Bray 1, respectively. In day 2, values were similar for both extraction methods (mean value 0.0027 mg DP L^{-1} mg^{-1} P kg). The soil P extraction coefficients values in TSP amendment plots were lower in Alzamora than in Corozal, due to the differences in clay contents which influences the soil P buffer capacity (Cox and Hendricks, 2000). Soils in Corozal had a lower P buffer capacity associated to a lower clay content and soil pH, and hence a greater P extraction coefficients.

Environmental critical STP values equal to 1 mg DP L^{-1} were obtained from STP-DP concentration relationships (Sharpley et al., 1996) and were presented in Table 7. The values obtained for PL amended plots were consistent with 90 mg kg^{-1} (Bray 1) determined by Andraski and Bundy (2003) for recently manured fields. In Alzamora and Corozal amended with TSP, the environmental critical STP levels coincided for Olsen STP, validating a level of 179 (±6) mg P kg^{-1} suggested in Puerto Rico by Sotomayor-Ramírez et al. (2004). In Corozal, a Bray 1 environmental critical level of 206 mg kg^{-1} in TSP amended soils agreed with the value of 197 (±7) mg P kg^{-1} suggested for Puerto Rico. In Alzamora, the Bray 1 environmental critical level of 143 mg P kg^{-1} in TSP amended soils, underestimated suggested critical STP level because of the lower P extraction capacity of the Bray 1 solution due to the increase in soil pH from TSP amendment.

CONCLUSIONS

The dissolved portion of P in runoff was the most important fraction of TP in soils with high groundcover and low slope; but the particulate fraction (TP minus DP fraction) was the most important fraction in soils with low groundcover and higher slopes. Soils amended with PL had higher TP and DP concentrations in runoff than soils amended with TSP at given STP levels. Within a given STP class level in soils with high groundcover and low slope, concentrations of TP and DP in runoff were reduced due to greater soil water content content and increased runoff duration. Mass losses of DP and TP were constant, but the SS and the PP discharge for a same STP and soil P loss susceptibility level increased due to daily change in soil moisture and runoff depth.

There was a reduction in the STP-DP relationship regression coefficient (R^2) in fields with organic amendment demonstrating that the time after to PL amendment needs to be considerate prior to using STP as a P loss predictor. Another factor which reduced R^2 values was the day effect, reflected in the antecedent soil moisture content, runoff depth, SS and possible PP increases in soils with high groundcover and low slope. These hydrologic effects show indicate that separate considerations need be given to P losses occurring in consecutive runoff event estimations (a wet day after dry day or a wet day after wet day). During the runoff event, SS concentrations increased and DP and TP concentrations decreased with highest values in the first 10 min of the runoff event. The effect of P dilution in runoff decreased with decreased STP category level. Soils with lower SS concentration in runoff had greater DP/TP ratio.

The calculated STP critical levels for Olsen and Bray 1 P inorganic amended fields validated the suggested values for tropical soils. However, soils with recent application time (< 6 mo) of TSP temporarily affected the soil pH and Bray 1 P extraction capacity. This condition favored a possible overestimation on soil P loss susceptibility and a suggested STP critical level. The STP environmental critical level is probably underestimated in soils with recent poultry manure application (< 6 mo) because the soil test was not representative of the soil P status due to the chemical effects generated for this amendment and organic residue present on surface soil and added to vegetation.

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Table 1. Physical and chemical properties for soils included in rainfall simulated studies in Alzamora (site 1) and Corozal (site 2) sites.

Soil P loss categorical level	**P amendment source (site)**					
	Organic Matter (%)			**pH**		
	TSP (1)	**PL (2)**	**TSP (2)**	**TSP (1)**	**PL (2)**	**TSP (2)**
Low	4.32 ab[1]	4.96	4.69	5.54 a	5.90 a	5.86 b
Medium	3.84 a	6.12**[2]	5.15*	5.52 a	6.47 b*	5.78 b
High	4.26 ab	5.28**	4.94*	6.72 b*	6.91 c*	5.19 a
Very High	5.15 b	5.84*	ND[3]	7.64 c	7.27 c	ND
Ext. High	5.22 b	5.72*	5.27	6.44 a	7.38 d*	6.35 c

[1] Values followed by the same letter are not significantly different (p<0.05) between soil P loss categorical levels for each Olsen and Bray 1 STP.

[2] Values with different symbol are significantly different (p<0.05) between sites and P amendment source. [3]ND indicates the no data is available.

Table 2. Hydrologic parameters generated in 70 mm hr^{-1} simulated rainfall intensity and 30 min runoff time in Alzamora (Site 1) and Corozal (Site 2) sites in Puerto Rico.

Parameter	Site 1 Inorg. P		Site 2 Inorg. P		Site 2 Org. P	
	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2
Time to runoff (t) (min)	15.0 a[1]	5.6 b	4.92 b	3.33 b	4.38 b	2.80 b
Runoff Depth (R) (mm)	15.1 b	25.5 a	20.27 a	25.48 a	20.29 a	28.72 a
Average flow (Q) (mm min^{-1})	0.52 b	0.85 a	0.68 a	0.85 a	0.68 a	0.96 a
Antecedent soil moisture (Θ) (%)	32.3 c	39.5 a	36.14b	40.77 a	36.26b	40.54 a
R/P ratio (%)	34.1 b	62.9 a	50.15 a	62.93 a	50.75 a	75.25 a
Suspended Solids (SS) g L^{-1}	0.17 b	0.18 b	0.67 a	0.66 a	0.65 a	0.64 a

[1] Values followed by the same letter are not significantly different ($p<0.05$) between days of simulation and P source amendment.

Table 3. Effect of STP category level and P source amendment on DP and TP concentrations (mg L^{-1}) in runoff from two sites with an intensity simulated rainfall of 70 mm h^{-1}.

Soil P loss categorical level	DP (mg L^{-1})							
	Olsen				Bray 1			
	TSP (1) Day 1	TSP (1) Day 2	PL (2)	TSP (2)	TSP (1) Day 1	TSP (1) Day 2	PL (2)	TSP (2)
Low	0.31 a[1]*	0.30 a*[2]	0.08 a	0.08 a	0.31 a*	0.22 a*	0.07 a	0.11 a
Medium	0.37 a*	0.19 a	0.13 a	0.19 a	0.39 a	0.31 a	0.385 a	0.26 a
High	0.60 ab*	0.36 a	1.20 ab**	0.48 a*	0.64 a**	0.36 a	0.93 ab*	0.48 a**
Very High	0.83 ab	0.45 a	2.38 b*	ND	1.44 b*	0.41 a	1.59 b*	ND
Ext. High	1.08 b	0.95 b	ND[3]	2.345 b*	1.73 b	1.12 b	2.96 c*	2.35 b**
	TP (mg L^{-1})							
Low	0.31 a	0.30 a	0.41 a	0.36 a	0.33 a	0.26 a	0.51 a	0.54 a
Medium	0.34 a	0.24 a	0.72 a*	0.84 ab**	0.50 a	0.43 a	0.795 a	0.75 a
High	0.73 ab*	0.48 a	2.95 ab***	1.58 b**	0.80 a*	0.56 a	2.56 ab***	1.58 a**
Very High	1.13 b*	0.69 a	5.55 b**	ND	1.61 b*	0.58 a	3.04 ab**	ND
Ext. High	1.57 b	1.27 b	ND	4.40 c*	2.06 b	1.81 b	7.12 b**	4.40 b*

1 Values followed by the same letter are not significantly different ($p<0.05$) between soil P loss categorical levels for each Olsen and Bray 1 STP.

2 Values with different symbol are significantly different ($p<0.05$) between sites, days (site 1) and P amendment source.

3 ND indicates the no data is available.

Table 4. Relationship between dissolved P (DP) in runoff and soil test P (STP) as fit by the equation $DP = a*b^{STP}$ for 10, 20 and 30 min. runoff durations in two sites amended two P sources. The day of simulation effect was only significant in Alzamora (site 1)

STP method	Runoff Time (min)	TSP (1) Day 1			TSP (1) Day 2			TSP (2)			PL (2)		
		a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2
	10	0.3929	1.0073	0.83	0.3163	1.0048	0.44	0.2631	1.0086	0.83	0.3273	1.0175	0.64
Olsen	20	0.3077	1.0072	0.87	0.2561	1.0051	0.57	0.1951	1.0092	0.82	0.3335	1.0156	0.57
	30	0.2720	1.0071	0.92	0.2288	1.0050	0.49	0.1768	1.0090	0.92	0.2714	1.0149	0.63
	10	0.5610	1.0068	0.80	0.4072	1.0043	0.40	0.2270	1.0086	0.90	0.4038	1.0119	0.72
Bray 1	20	0.4461	1.0066	0.85	0.3386	1.0045	0.50	0.1030	1.0105	0.90	0.3961	1.0109	0.68
	30	0.3836	1.0067	0.87	0.2972	1.0044	0.43	0.1368	1.0087	0.90	0.3278	1.0101	0.67

Table 5. Relationship between dissolved P in runoff (DP), volumetric soil moisture, organic matter and soil test phosphorus.

STP method	**Site and Amendment condition**	**Equation**	R^2
Olsen	Inorg. P	DP= 0.4255+0.0056*Olsen - 1.0525*Θ	0.62
	Org. P	DP= -1.1801+0.0175*Olsen + 2.6505*Θ	0.68
Bray 1	Inorg. P	DP= 0.3566+0.0055*Bray 1 - 0.3538*Θ	0.63
	Org. P	DP= -1.3788+0.0130* Bray 1 + 3.5872*Θ	0.76
Olsen	Inorg. P	DP= -0.1924+0.0053*Olsen + 0.0559*OM	0.60
	Org. P	DP= 2.3071 + 0.0176*Olsen – 0.4931*OM	0.71
Bray 1	Inorg. P	DP= -0.1438 + 0.0053*Bray + 0.0828*OM	0.63
	Org. P	DP= 1.4379 + 0.0131*Bray – 0.2774*OM	0.76

Table 6. Effect of soil test P categorical level and P source amendment on DP and TP mass losses (g m^{-2}) in runoff from two sites with an intensity simulated rainfall of 70 mm h^{-1}.

Soil P loss categorical level	**DP (g m^{-2})**					
	Olsen			**Bray 1**		
	TSP (1)	**PL (2)**	**TSP (2)**	**TSP (1)**	**PL (2)**	**TSP (2)**
Low	0.056 a[1]	0.017 a	0.017 a	0.075 a	0.015 a	0.022 a
Medium	0.089 a	0.036 a	0.052 a	0.096 a	0.100 ab	0.082 a
High	0.103 a‡[2]	0.247 ab	0.096 a‡	0.112 ab	0.224 ab	0. 095 a‡
Very High	0.148 ab	0.543 b	ND	0.166 b	3.69 ab	ND
Ext. High	0.205 b	ND[3]	0.538 b	0.219 b	0.736 b	0.538 b‡
	TP (g m^{-2})					
Low	0.071 a	0.089 a	0.087 a	0.084 a	0.119 a	0.134 a
Medium	0.076 ab	0.191 a	0.219 ab	0.131 ab	0.262 a	0.271 a
High	0.132 abc	0.642 ab	0.317 b‡	0.153 ab	0.598 a	0.305 a‡
Very High	0.214 bc	1.307 b	ND	0.260 b	0.700 a	ND
Ext. High	0.269 c	ND	1.045 c	0.289 b	1.949 b	0.831 b‡

[1] Values followed by the same letter are not significantly different ($p<0.05$) between soil P loss categorical levels.

[2] Values with different symbol are significantly different ($p<0.05$) between sites and P amendment source. [3]ND indicates the no data is available.

Table 7. Environmental soil test P critical level for two P amendment sources and two extraction methods in Alzamora and Corozal sites.

STP	Alzamora	Corozal	
	TSP	**TSP**	**PL**
Olsen	184	176	88.5
Bray 1	143	206	112

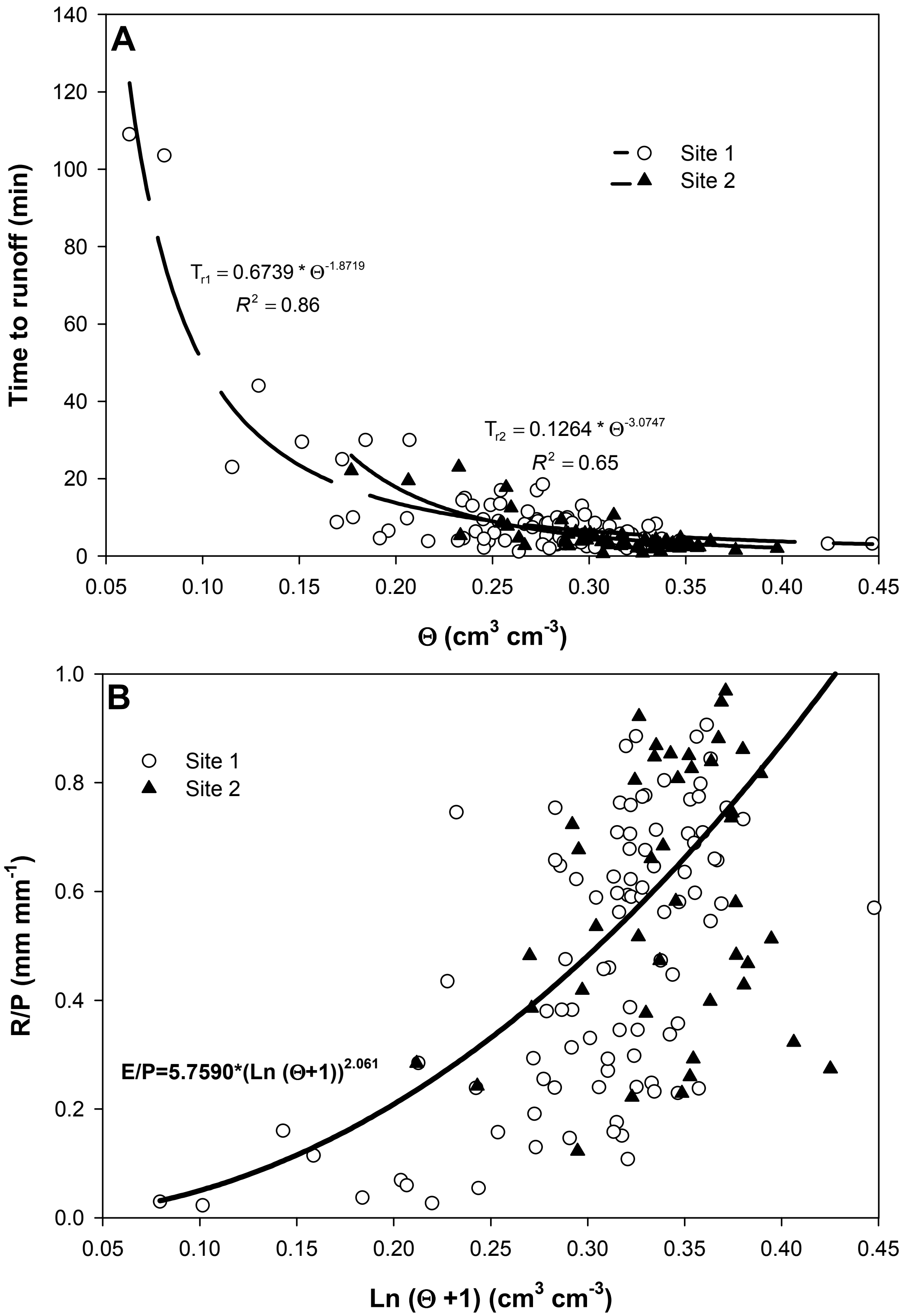

Figure 1. (A) Antecedent soil moisture – time to runoff start relationship and (B) Antecedent soil moisture – runoff-rainfall ratio relationship on 70 mm hr^{-1} simulated rainfall.

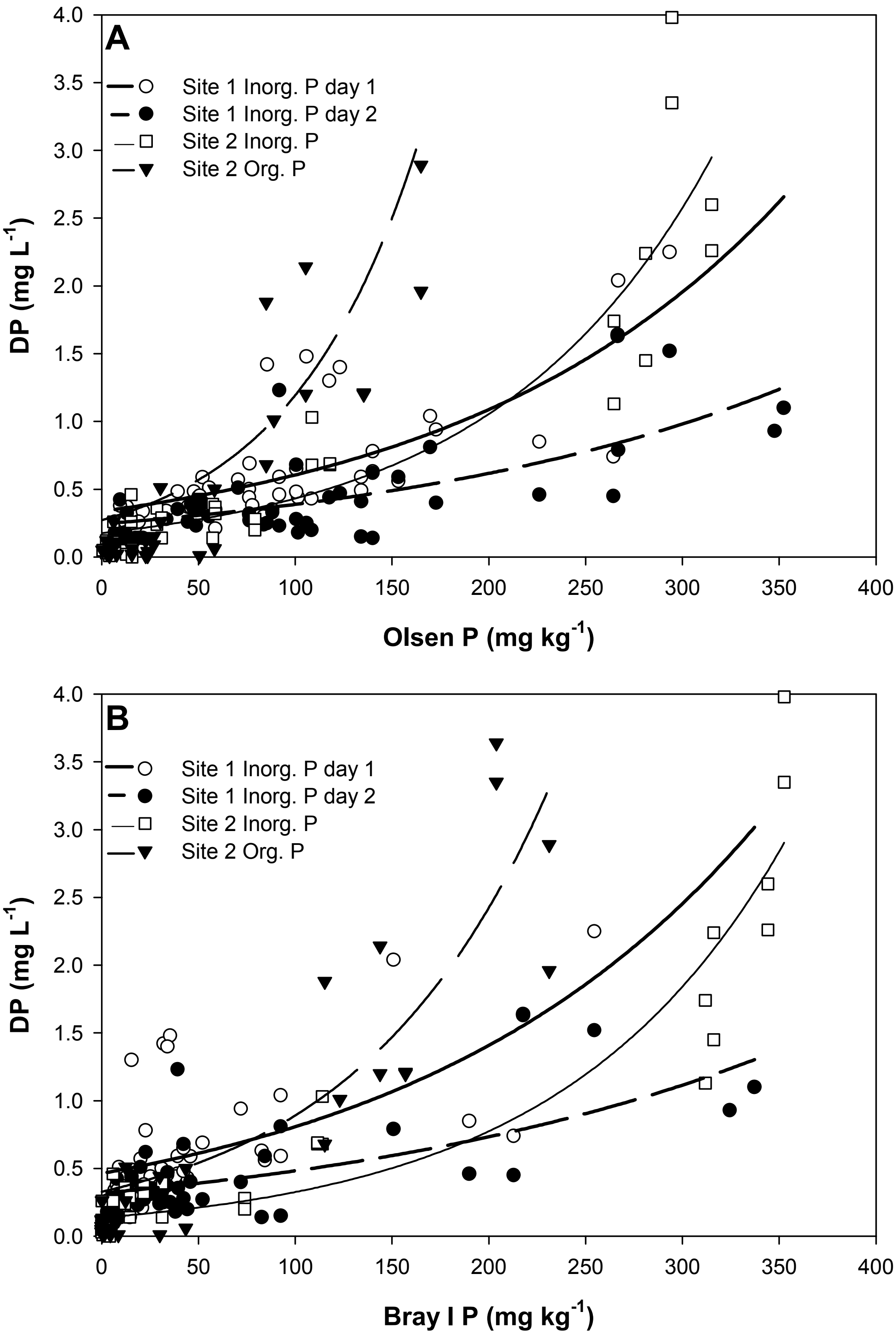

Figure 2. STP-DP relationship in 30 min runoff for Olsen (A) and Bray 1 (B) P extraction method on P different amendmend conditions and simulation day.

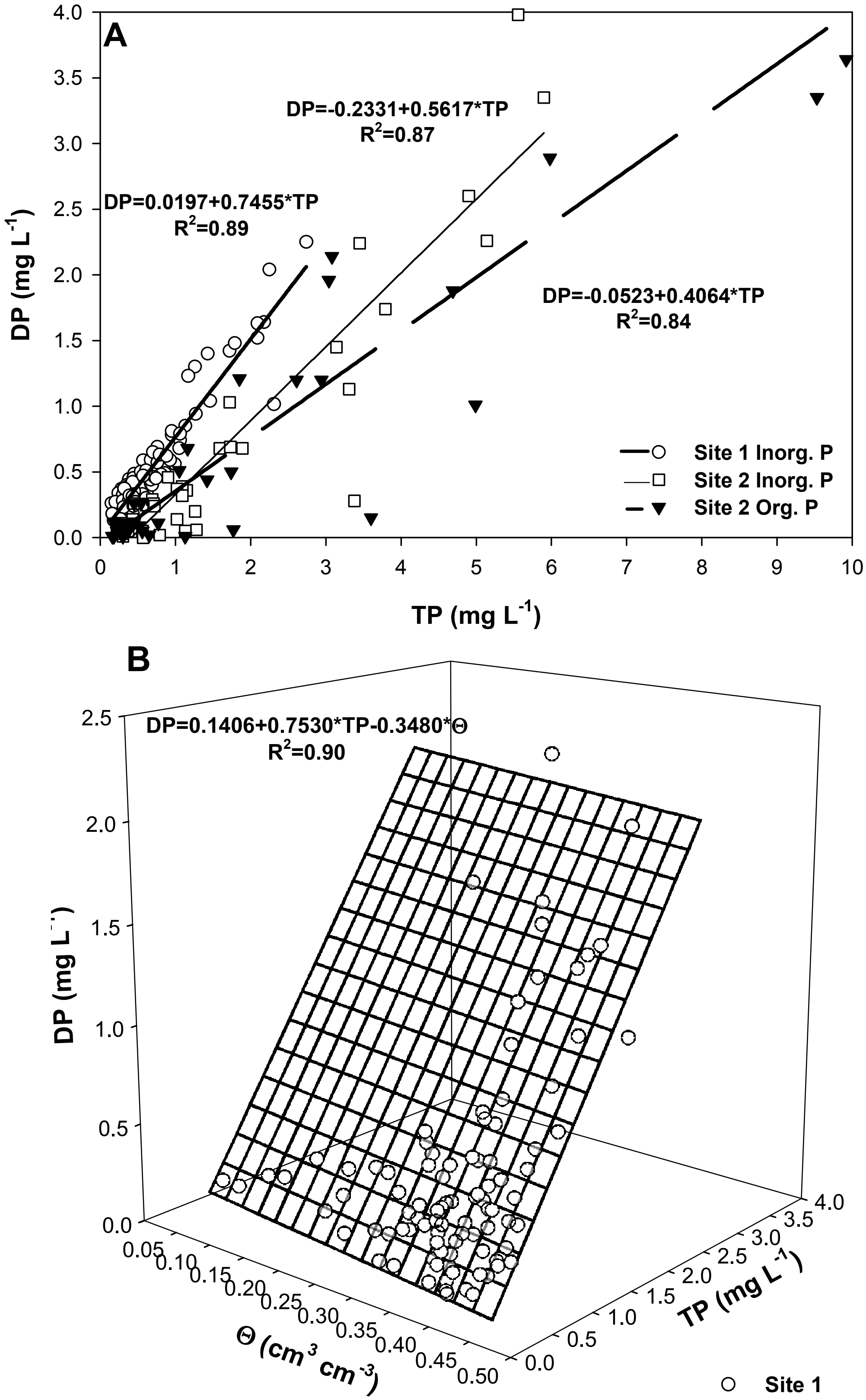

Figure 3. Runoff DP-TP relationships in Alzamora and Corozal (A), and effect of soil moisture (B) on TP-DP runoff relationship for different amend conditions in Alzamora (site 1).

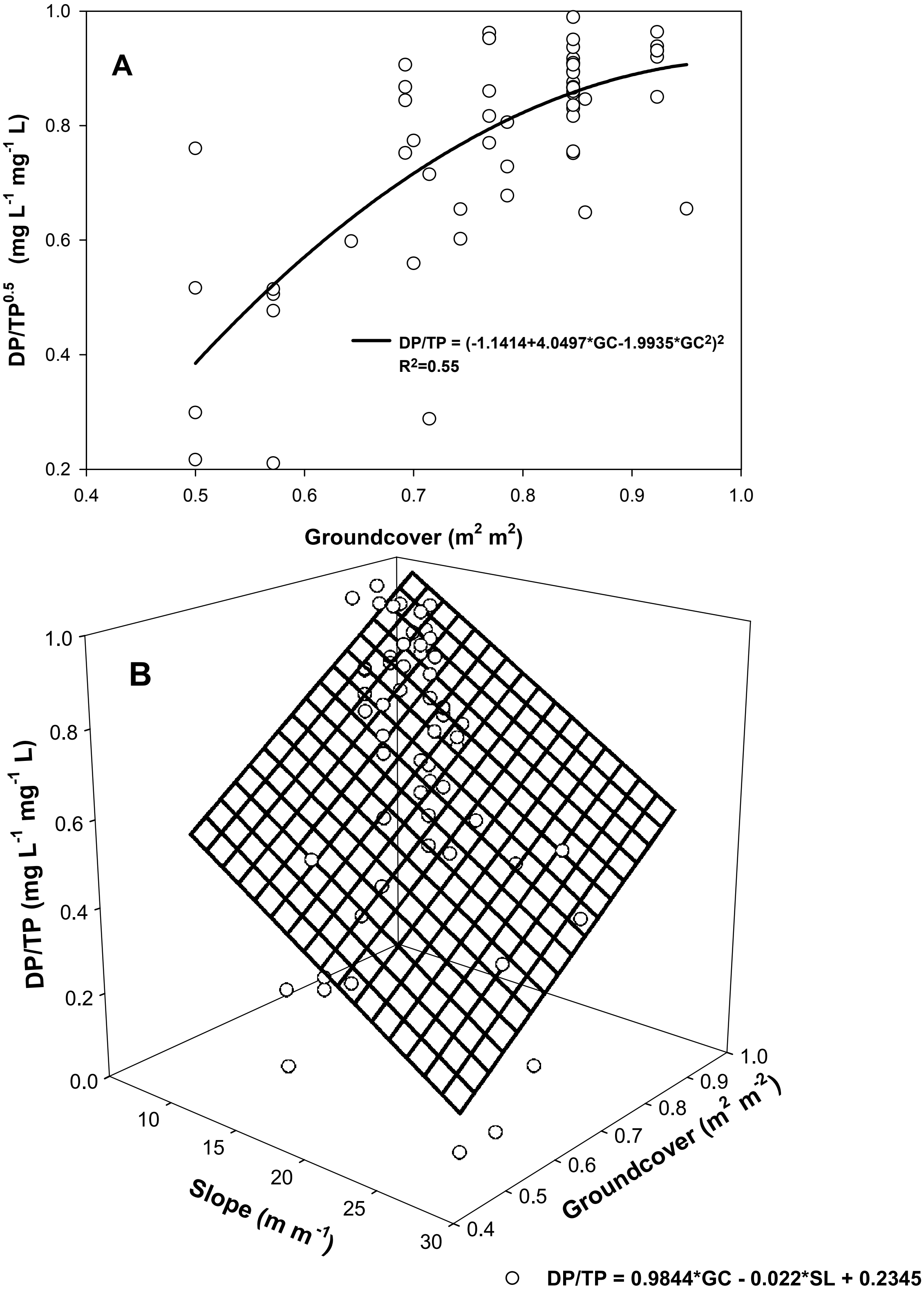

Figure 4. (A) Groundcover effect on DP/TP ratio of P in runoff and (B) combined groundcover and slope effects on DP/TP ratio.

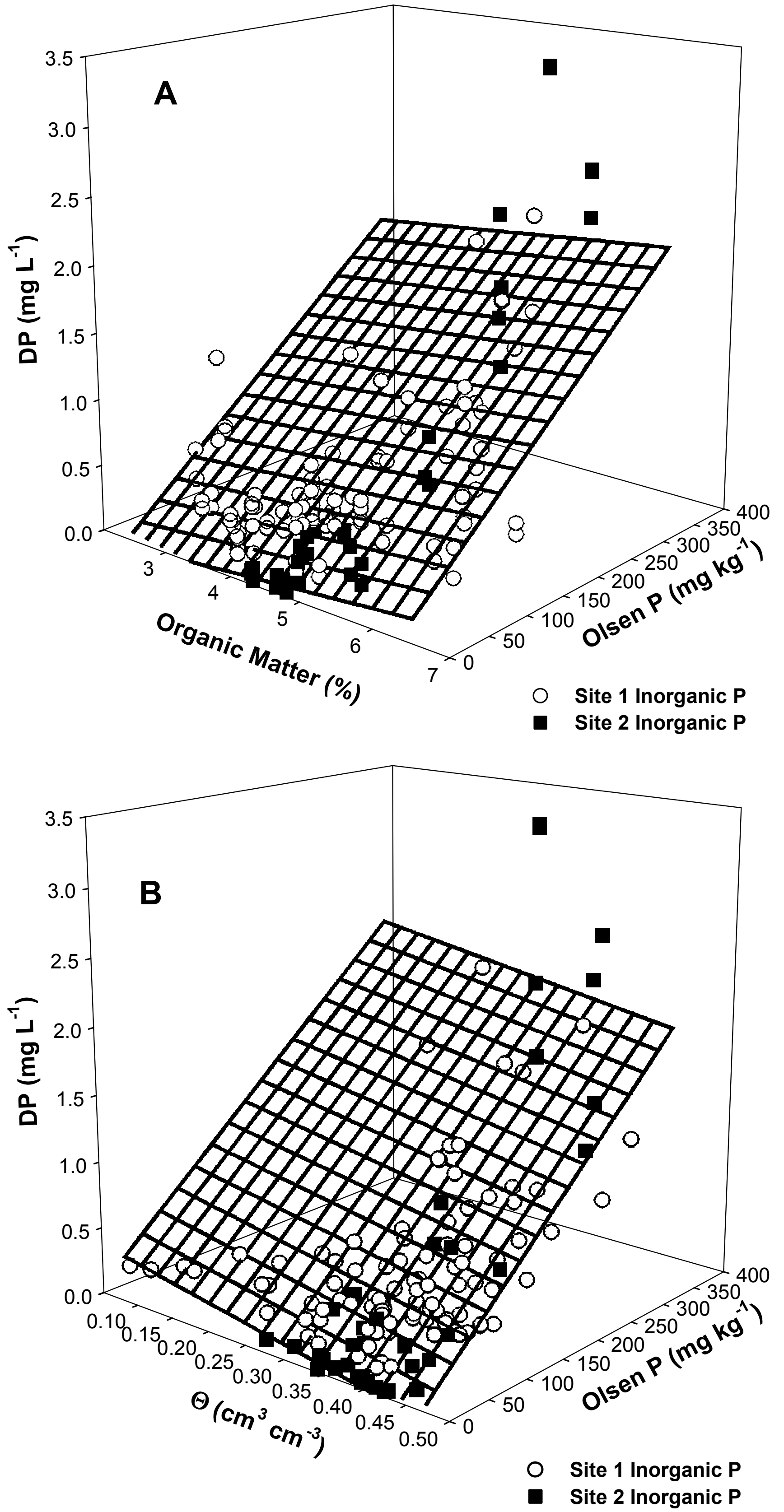

Figure 5. Organic matter effect on STP-TP relationship (A), and antecedent soil moisture content effects on STP-DP relationship (B) on inorganic P amend plots.

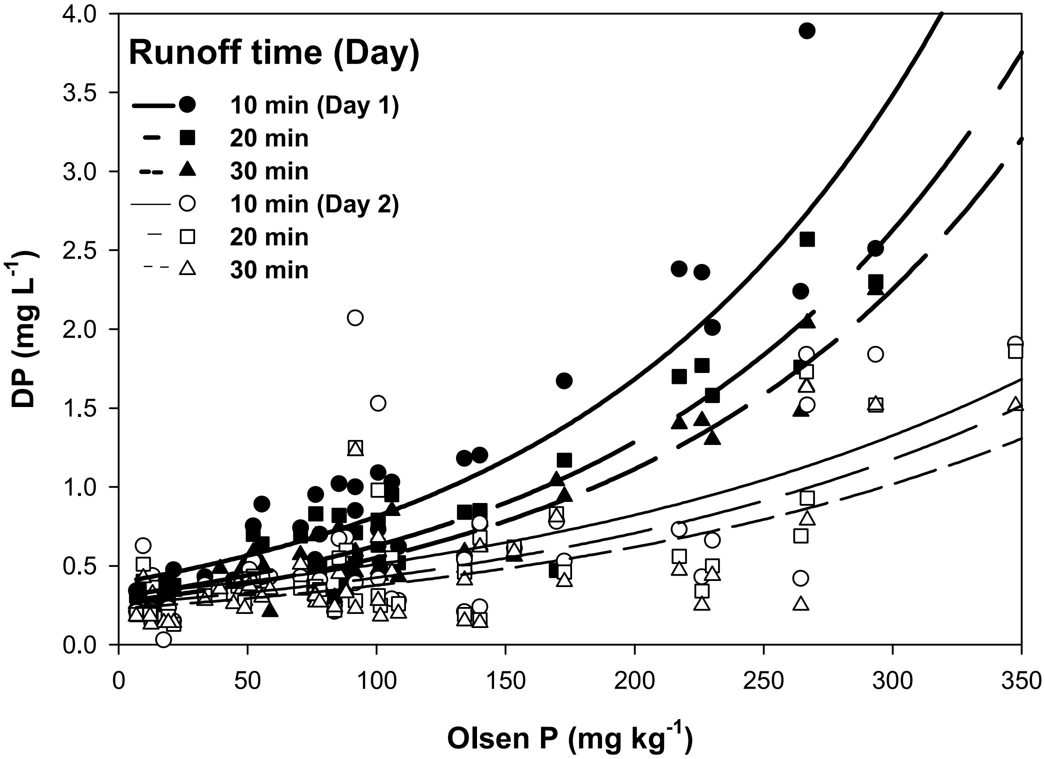

Figure 6. Runoff duration and simulation day effects on STP-DP relationship.

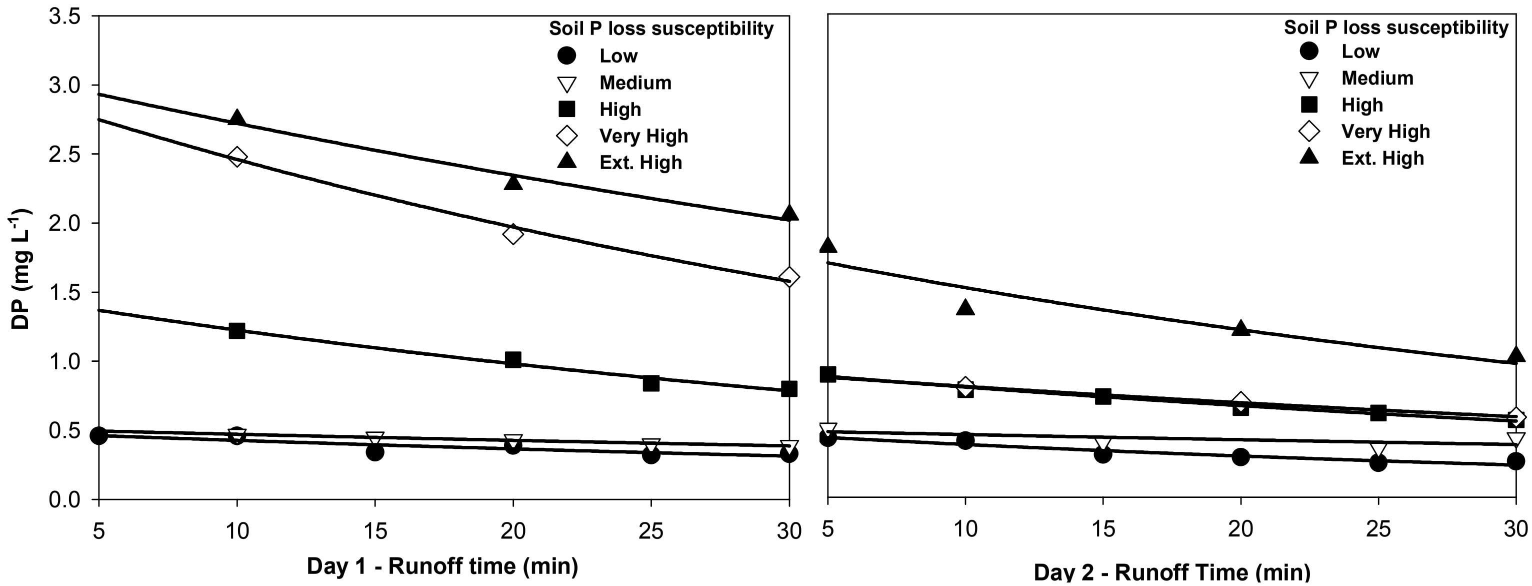

Figure 7. Runoff duration and soil P loss susceptibility level effects on DP concentration in two simulation days in Alzamora site.