Determining Phosphorus and Sediment Release Rates from Five Irish Tillage Soils

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The aim of this study was to compare the nutrient and sediment releases from five Irish tillage soils, inclined at 10- and 15-degree slopes, under a simulated rainfall intensity of 30 mm h^{-1} in a controlled laboratory study. Using the relationship between soil test phosphorus (STP) in the five soils and the dissolved reactive phosphorus (DRP) released in surface runoff, a runoff dissolved phosphorus risk indicator (RDPRI) was developed to identify the STP level for Irish tillage soils above which there may be a potential threat to surface water quality. The results of this study indicated that tillage soils may produce surface runoff P concentrations in excess of 30 μg L^{-1} (the value above which eutrophication of rivers is likely to occur and the maximum allowable concentration of DRP in rivers under the EU Water Framework Directive, WFD) if their Morgan's phosphorus (P_m), Mehlich 3 phosphorus (M3-P), and water extractable phosphorus (WEP) concentrations exceed 9.5 mg L^{-1}, 67.2 mg kg^{-1}, and 4.4 mg kg^{-1}, respectively. This work reinforces the statutory agronomic based requirements of the European Communities (Good Agricultural Practice for Protection of Waters) Regulations 2009 (S.I. no. 101 of 2009). A statistical analysis showed that WEP gave the best prediction for runoff DRP.

Dissolved reactive phosphorus is readily available for biological uptake, and poses an immediate threat for accelerated algal growth which may negatively affect water quality in rivers and lakes. In 2002, the World Health Organization (WHO) (WHO, 2002) reported that when P is the limiting factor, a phosphate concentration of 10 μg L^{-1} is enough to support plankton, and concentrations from 30 to 100 μg L^{-1}, or higher, will be likely to promote algal blooms. In Ireland, empirical comparison of in-stream phosphate levels and biological quality has demonstrated that once median phosphate concentrations exceed 30 μg L^{-1} P, significant deterioration is seen in river ecosystems (Clabby et al., 2008).

Phosphorus loss in surface runoff from soils is an important pathway in many agro-environments (Sims et al., 2002; Wright et al., 2006). A survey of 1151 rivers in Ireland from 2004 to 2006 (Clabby et al., 2008) estimated that the amount of pollution attributed to agriculture was approximately one-third. In Europe, a review of the contribution of agriculture to pollution in rivers suggests that it is contributing approximately one-third of all P (de Wit et al., 2002). In contrast, Carpenter et al. (1998) estimated that 84% of all P discharged to surface waters in the United States originated from nonpoint sources. The EU WFD (2000/60/EC; CEC, 2000) aims to restore polluted water bodies to at least "good ecological status" (< 30 μg P L^{-1} in rivers) by 2015 and prevent any further deterioration in the status of surface waters, groundwater, and water-dependent ecosystems.

Tillage crops cover about 10% of land area farmed in Ireland, whereas they account for 26% of fertilizer use (Lee, 1986). Furthermore, arable cropping, due to its intensive nature, can leave soil with reduced ground cover and impaired soil structure, making it vulnerable to erosion under heavy rainfall. To date, in Ireland, no study has investigated the link between erosion and P loss from tillage soils. As a result, only agronomic nutrient advice is available and this has been adopted into the European Communities (Good Agricultural Practice for Protection of Waters) Regulations 2009 (S.I. no. 101 of 2009). In Ireland, Morgan's soil P test (Morgan, 1941) is used as the national soil P test with the current agronomic

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Abbreviations: DRP, dissolved reactive phosphorus; FWMC, flow-weighted mean concentration; GLMM, generalized linear mixed model; M3-P, Mehlich 3 phosphorus; P_m, Morgan's phosphorus; PP, particulate phosphorus; RDPRI, runoff dissolved phosphorus risk indicator; SS, suspended sediment; STP, soil test phosphorus; TP, total phosphorus; WEP, water extractable phosphorus.

optimum P_m value for Irish tillage soils falling between 6.1 to 10 mg L^{-1}, while a M3-P of 50 mg kg^{-1} (approximately 8 mg L^{-1} as P_m) is generally considered to be optimum in the United States. Given that tillage soils receive higher levels of fertilizer and are more susceptible to erosion than grassland soils, they have greater pollution potential. Research is necessary to assess the potential P losses arising from following agronomic advice.

The relationship between STP and DRP loss to water in runoff events needs to be adequately understood and quantified for local soils (Wright et al., 2006) to determine upper critical limits for P in soil that will reduce the risk of diffuse losses from tillage land to surface waters. The research detailed herein may help in identifying tillage soils in Ireland and elsewhere where STP is at a critical level and is likely to result in eutrophication of surface waters.

A laboratory flume study was chosen over a field study as soils in flume studies can be homogenized minimizing variability in soil physical and chemical characteristics. It is also less expensive and facilitates testing under standardized conditions including surface slope, soil conditions, and rainfall intensity. The expensive nature of field experiments and inherent variability in natural rainfall has made rainfall simulators and laboratory microcosms a widely used tool in P transport research (Hart et al., 2004) in particular, when attempting to estimate the magnitude of potential loses from different land management systems, soil types, and landscapes.

The aim of this paper is: (i) to quantify the amount of DRP, particulate phosphorus (PP), total phosphorus (TP) and suspended solids (SS) released in surface runoff from five tillage soils of varying P_m when subject to a rainfall intensity of 30 mm h^{-1} applied in three successive events; (ii) to rank the importance of soil physical and chemical parameters, in addition to surface slope and time interval between storm events, in the prediction of nutrient and sediment releases; and (iii) to develop a RDPRI for tilled soils in Ireland.

Materials and Methods

Soil Collection and Preparation

Fifteen tillage field sites, spread across Ireland, were investigated to find suitable soils with wide ranging physical and chemical properties. After preliminary characterization, five soils were then selected based on soil type, STP, particle size distribution (PSD), tillage history, and evidence of prior erosion problems. The soils selected were from: (i) Tullow, County Carlow; (ii) Clonmel, County Tipperary; (iii) Letterkenny, County Donegal; (iv) Bunclody, County Wexford; and (v) Fermoy, County Cork. The sites selected were in tillage for a minimum of 15 yr. The soils had a P_m index of 1 to 4 and ranged from 2.8 to 17.5 mg L^{-1} (Table 1). The P_m values broadly reflected the P fertilizer history of the five sites. The soils (Fermoy and Letterkenny) with low P_m (2.8 and 4.8 mg L^{-1}, respectively) received P fertilizer below the recommended agronomic levels over their rotation history, while those (Bunclody, Clonmel, and Tullow) with medium and very high P_m (7.1, 15.8, and 17.5 mg L^{-1}, respectively) received P fertilizer above agronomic levels. The Clonmel and Tullow soils had a history of receiving above 40 kg P ha^{-1} yr^{-1} in excess of crop requirement.

A sample of the plow layer of each of the five tilled soils was collected, air-dried, sieved (< 5 mm), and thoroughly mixed for use in a rainfall simulation study. This strategy was similar to that adopted by Miller et al. (2009). Other studies by Sharpley (1980) and Fang et al. (2002) used soils sieved to < 4 mm in flume studies to determine the effect of storm interval on DRP in runoff and to estimate runoff P losses, respectively. Subsamples of each soil were further sieved (< 2 mm) for physical and chemical characterization.

Simulated Rainfall Study

A runoff experiment was designed to compare the nutrient and sediment releases from the five soils when subjected to high intensity (30 mm h^{-1}), low energy rainfall. This experiment used two laboratory flumes, 200-cm-long by 22.5-cm-wide by 5-cm-deep with side walls 2.5 cm higher than the soil surface, and 5-mm diam. drainage holes, drilled in triplicate and located at 300-mm-centers, in the base. Cheese cloth was placed at the base of each flume before packing to prevent soil loss. Soils were packed to achieve an approximate bulk density of 1.3 to 1.5 g cm^{-3}. The packed soil was then saturated using a rotating disc, variable-intensity rainfall simulator (after Williams et al., 1997), and left to drain for 24 h before the experiment commenced. All soils were approximately at field capacity before the first rainfall event.

The rainfall simulator consisted of a single 1/4HH-SS14SQW nozzle (Spraying Systems Co., Wheaton, IL) attached to a 4.5-m-high metal frame, and calibrated to achieve an intensity of 30 mm h^{-1} and a droplet impact energy of 260 kJ mm^{-1} ha^{-1} at 85% uniformity. The return period for a 30 mm h^{-1} rainfall event ranged from 30 to 100 yr across the selected soil locations.

The source water for the rainfall simulations was potable tap water with a maximum DRP concentration of 0.005 mg L^{-1}. The tap water had an electrical conductivity (EC) = 0.421 dS m^{-1}, measured using a conductivity meter, and a Ca^{2+}, Mg^{2+}, and Na^{2+} concentration of 3.11, 2.24, and 22.55 mg L^{-1}, respectively, measured by atomic absorption spectrophotometry (AAS). Each rainfall simulation comprised three successive 1-h rainfall events at time zero (Rainfall 1), 1-h (Rainfall 2) and 24-h (Rainfall 3) to determine the effect of storm interval on surface runoff. During the rainfall simulation, six drainage holes remained open to better replicate field conditions. Each soil was examined at two slopes, 10 and 15 degrees, to investigate the effect of slope on nutrient and sediment losses in the runoff. Surface runoff samples were collected when runoff began: once every 2.5 min for the first 20 min and in each subsequent 5-min interval to evaluate changes in runoff volume, and nutrient and sediment concentration over time.

Soil and Runoff Analysis

The soil characteristics measured were: (i) pH; (ii) PSD by sieve and pipette analysis; and (iii) P_m. The filtered extracts were analyzed colorimetrically for P; (iv) soil organic matter (SOM) by loss on ignition (LOI) at 550°C; (v) ammonium oxalate-oxalic acid extractable phosphorus (P_{ox}), aluminum (Al_{ox}), iron (Fe_{ox}) measured by inductively coupled plasma–atomic emission spec-

Table 1. Chemical and physical properties of selected Irish tillage soils.†

Location	Soil type	pH	P_m	CEC	AgSt	$CaCO_3$	OM	Sand	Silt	Clay	M3-P	$Pcacl_2$	WEP	P_{ox}	Al_{ox}	Fe_{ox}	$Psat_{ox}$
			mg L^{-1}	cmol kg^{-1}	%	g kg^{-1}					mg kg^{-1}						%
Tullow, Co. Carlow	GBP	6.9	17.5	13.4	96.4	5	49	579	267	154	96.3	3.0	11.5	566	1033	3482	18.1
Clonmel, Co. Tipperary	GBP	6.7	15.8	11.2	90.0	5	42	528	306	167	89.4	2.1	6.6	457	903	3867	14.4
Bunclody, Co. Wexford	BP	7.7	7.1	13.9	92.9	26	71	410	387	203	58.7	1.0	3.5	414	2560	4755	7.4
Letterkenny, Co. Donegal	BP	6.5	4.8	13.7	98.5	17	55	491	395	114	52.1	1.3	2.8	592	1700	5468	11.9
Fermoy, Co. Cork	ABE	6.4	2.8	13.1	97.8	4	51	569	286	145	29.1	1.4	2.3	273	1227	3886	7.7

† GBP, grey brown podzolic; BP, brown podzolic; ABE, acid brown earth; OM, organic matter by loss on ignition; CEC, cation exchange capacity; P_m, P determined by Morgan's extraction; M3-P, Mehlich-3 extractable P; $Pcacl_2$, calcium chloride extractable P; WEP, water extractable P; P_{ox}, ammonium oxalate extractable P; Al_{ox}, ammonium oxalate extractable Al; Fe_{ox} ammonium oxalate extractable Fe; $Psat_{ox}$, soil P saturation as determined by ammonium oxalate extraction; AgSt, aggregate stability.

troscopy (ICP–AES). Soil P saturation ($Psat_{ox}$) was calculated as P_{ox} (mmol kg^{-1}), divided by Al_{ox} and Fe_{ox}, and multiplied by 100; (vi) WEP was measured by shaking 0.5 g of soil in 40 mL of distilled water for 1 h, filtering (0.45 μm) the supernatant water and determining P colorimetrically; (vii) M3-P (Mehlich, 1984); (viii) cation exchange capacity (CEC; Bascomb, 1964); (ix) calcium carbonate ($CaCO_3$) was determined by the volumetric method (International Organisation for Standardisation, 1995; ISO 10693); (x) calcium chloride extractable P ($CaCl_2$ ex P) by extraction with 0.01 mol L^{-1} $CaCl_2$; (xi) aggregate stability (AgSt) was determined using a wet sieving apparatus. The coefficient of variation of P_m for each soil was < 0.05, thus ensuring homogeneity of the soils.

Immediately after collection, runoff water samples were filtered (0.45μm) and analyzed colorimetrically for DRP using a nutrient analyzer (Konelab 20, Thermo Clinical Labsystems, Finland). Runoff water samples were frozen at –20°C until TP was conducted. The TP was determined for every second runoff sample after acid persulfate digestion. Total P comprises both PP and total dissolved phosphorus (TDP). The PP was calculated by subtracting DRP from TP. As tests indicated that TDP was similar to DRP in the runoff water, and two orders of magnitude smaller than TP, this simplification was deemed appropriate. Suspended sediment were determined for all samples by vacuum filtration of 50 mL of well-mixed runoff water through Whatman GF/C (pore size 1.2 μm) filter paper. All samples were tested in accordance with the Standard Methods (American Public Health Association, 2005).

Statistical Methods

A generalized linear mixed model (GLMM) was fitted to each surface runoff response to test whether the effect of soil type depends on slope and rainfall event. A random effect with a first-order autoregressive variance-covariance structure was fitted to account for nonindependence of successive rainfall events (The GLIMMIX Procedure, SAS V9.1, SAS Institute, 2004). A log link function was required for all surface runoff responses to satisfy the assumption of normality of residuals. When investigating P transport in surface runoff from packed soil boxes, Kleinman et al. (2004) also logarithmically transformed P concentrations.

The inclusion of soil type as a factor in the GLMM allows quantification of the variation due to soil, so that we can then determine how much of this variation is accounted for by the different soil characteristic parameters. For DRP, the effect of soil type differed depending on slope and rainfall event. A stepwise regression selection procedure was subsequently conducted for each slope-rainfall combination to determine which characteristics were important in explaining variation in DRP. For SS, TP, and PP, the stepwise procedure was performed separately for each slope, as the effects of soil type differed depending only on slope.

A RDPRI was developed using the relationship between FWMC of DRP released in the surface runoff and each of P_m, M3-P, and WEP. This was achieved by constructing 95% confidence bands around the DRP relationships using the upper and lower prediction limits for the linear predictor. The resulting confidence bands were then back-transformed from the log-linear model to the original scale to identify the level of each P measure above which there may be a potential threat to surface water quality.

Results and Discussion

Soil Characteristics

Selected soil chemical and physical properties are shown in Table 1. Particle size analysis showed that sand was the dominant size fraction across the five soils. The basic soil textural class ranged from loam to sandy-loam, with sandy-loam dominating. This was representative of tillage which predominates in the east and south of Ireland, where soils are highly suited to tillage, and generally have a light-to-medium texture, friable consistence, and free drainage (Gardiner and Radford, 1980). Heavier textured soils are less suitable for tillage in Ireland as they often occur at higher elevations leading to slope problems, weak structure, and are imperfectly drained (Gardiner and Radford, 1980).

If an agronomic soil P test is to be used for environmental purposes, it is important that it be well correlated with the forms of soil P most susceptible to losses in surface runoff and with soil P saturation (Sims et al., 2002). The M3-P was well correlated with P_m (r = 0.98), WEP (r = 0.89), $Psat_{ox}$ (r = 0.86), and $Pcacl_2$ (r = 0.80). The WEP was well correlated with P_m (r = 0.92), $Psat_{ox}$ (r = 0.9), and $Pcacl_2$ (r = 0.95). $Pcacl_2$ correlated well with P_m (r = 0.87) and $Psat_{ox}$ (r = 0.93). The $Psat_{ox}$ correlated well with P_m (r = 0.87).

Suspended Sediment and Phosphorus Concentrations in Runoff

Generally, the highest SS and nutrient concentrations occurred within 15 min of the commencement of surface runoff and reached steady state after 30 min of the commencement of the first rainfall event (Fig. 1 and 2). The high DRP concentra-

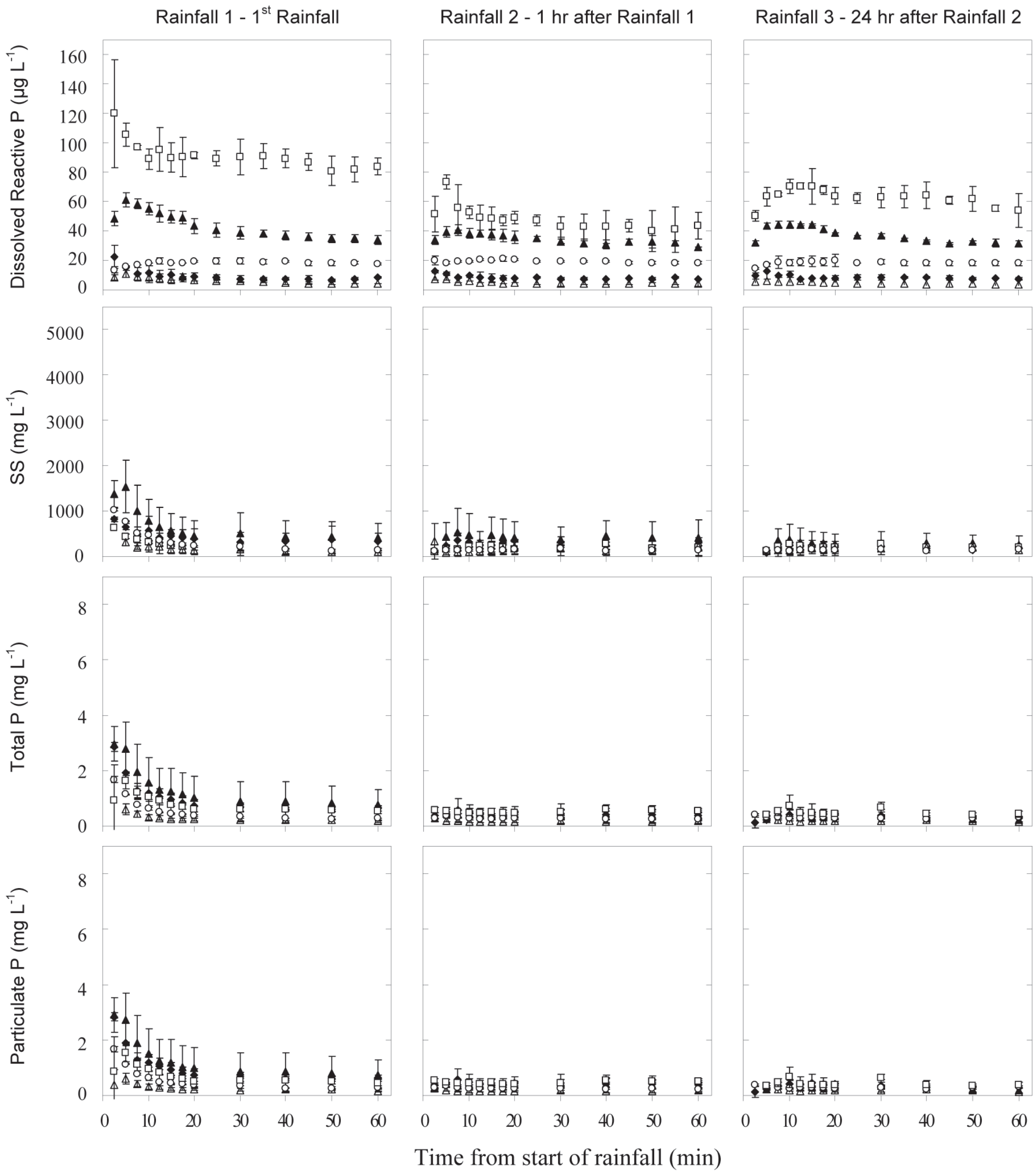

Fig. 1. Phosphorus and sediment losses over time from tillage soils inclined at a 10 degree slope. Clonmel (closed triangle), Tullow (open square), Letterkenny (closed diamond), Bunclody (open circle), Fermoy (open triangle).

tion in runoff at the start of a storm event may partly be explained by dilution as a function of runoff rates, which did not reach equilibrium until 5 min into a rainfall event. In addition, given that soils were pre-wet for up to 24 h before rainfall commenced, a larger portion of the readily soluble and more slowly soluble P forms may have reached solution, thus elevating P levels in the soil water. As the rainfall event proceeded, the older pre-wet water becomes diluted by clean simulation water resulting in a reduction in runoff DRP concentration. Soils with high concentrations of extractable soil P had the highest concentration of DRP in surface runoff (Fig. 1). The FWMC of DRP in surface runoff from the Tullow and Clonmel soils peaked at 90 and 42 µg L^{-1}, respectively, during the first rainfall event and, as such, may negatively affect water quality.

The potential for particulate losses in surface runoff was found to be high for the five soils, with the highest from the Clonmel soil, where peak SS and PP concentrations of 4263 and 5.99 mg L^{-1}, respectively, were measured (Fig. 2). This is in agreement with Fang et al. (2002) who reported that PP contributed from 59 to 98% of total runoff P for unvegetated packed boxes. As PP is generally bound to the minerals (particularly Fe, Al, and Ca) and organic compounds contained in soil, it constitutes a long-term P reserve of low bioavailability. Albeit nutrients lost in surface runoff from packed boxes are broadly consistent with those lost from field plots, the exposed bare soils of packed boxes are vulnerable to erosion resulting in greater PP concentrations in runoff (Kleinman et al., 2004). The PP and SS losses measured in surface runoff during this study may represent a worst case scenario because of the steep slope (typical of sites where a P loss risk assessment is necessary), high rainfall intensity (typical of storm events), and bare soil with reduced aggregate stability compared to in situ soil. It

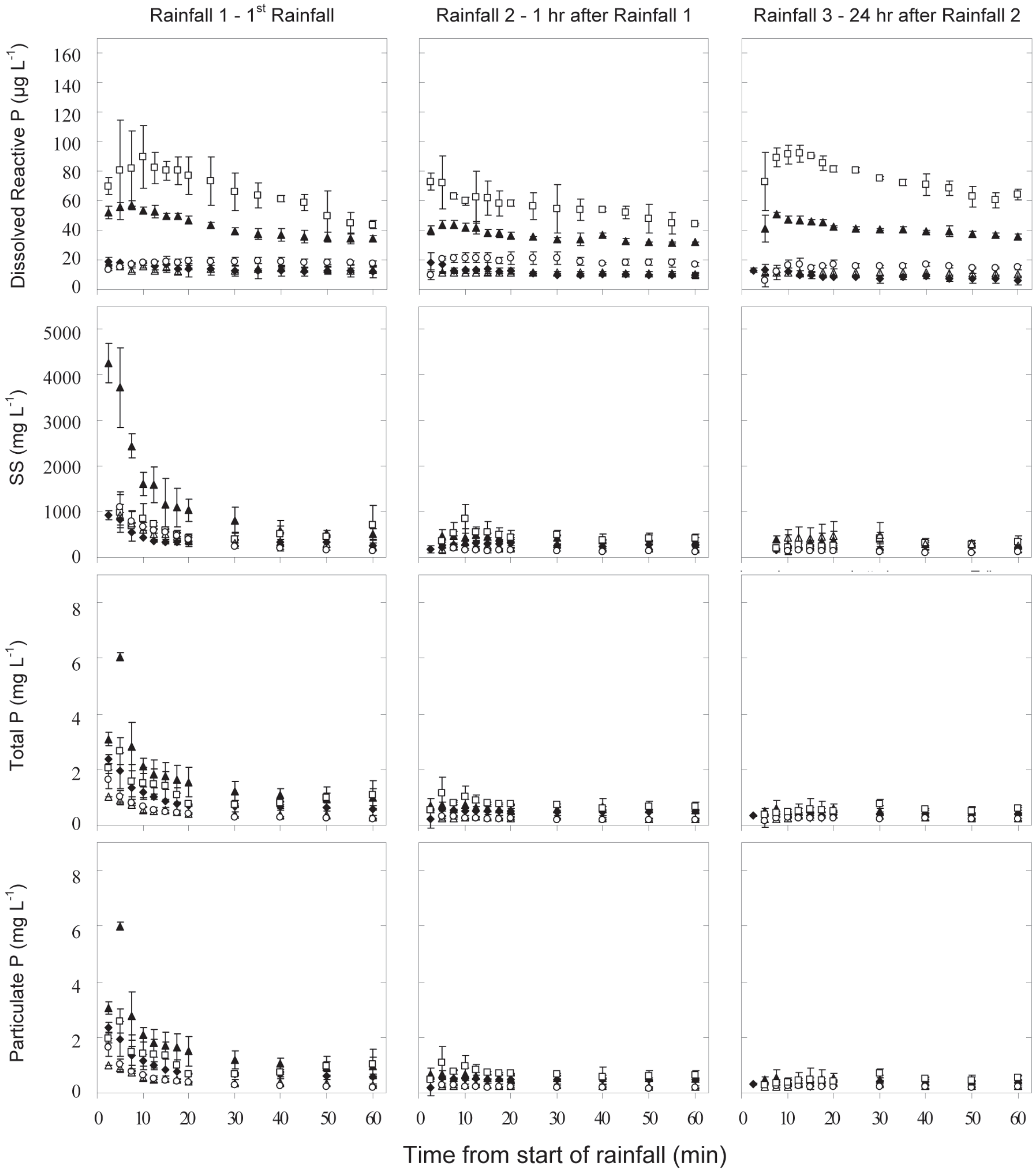

Fig. 2. Phosphorus and sediment losses from selected tillage soils inclined at a 15 degree slope. Clonmel (closed triangle), Tullow (open square), Letterkenny (closed diamond), Bunclody (open circle), Fermoy (open triangle).

is unlikely that SS and PP edge of field losses from these soils in situ would be so high given the variable surface slope, and proximity to surface waters. Recognized management practices, namely, riparian buffer strips, conservation tillage, and contour plowing, where used, are also effective in controlling PP loss from agricultural fields.

A Method for Identifying the Critical Soil Test Phosphorus Threshold above which Runoff Water May Pose a Threat to Surface Water Quality

Eutrophic symptoms in rivers are commonly linked to transient increases in DRP concentrations during times of ecological sensitivity (Jarvie et al., 2006). A critical STP threshold must exist above which runoff water will negatively affect surface water quality. A RDPRI was developed in this study to identify a STP threshold (measured in terms of P_m, M3-P, and WEP) above which runoff water across the five soils tested will have a DRP concentration > 30 μg P L^{-1}. Present nutrient advice for tillage crops in Ireland prohibits the application of fertilizer or manure at P_m concentrations above 10 mg L^{-1} (S.I. no. 101 of 2009) with the exception of potatoes (*Solanum tuberosum* L.), beet (*Beta vulgaris* L.), and turnips (*Brassica rapa*). This limit is based on crop yield response to fertilizer P, but needs to be assessed from an environmental standpoint. The RDPRI enables this assessment to be performed.

The logarithm of the FWMC of DRP in surface runoff from each soil was linearly related to P_m of each soil for all rainfall events (Fig. 3). The logarithm of the FWMC of DRP in surface runoff from each soil was also linearly related to WEP and M3-P levels in each soil for all events (data not shown). The DRP lost to runoff water increases log-linearly as P_m, WEP,

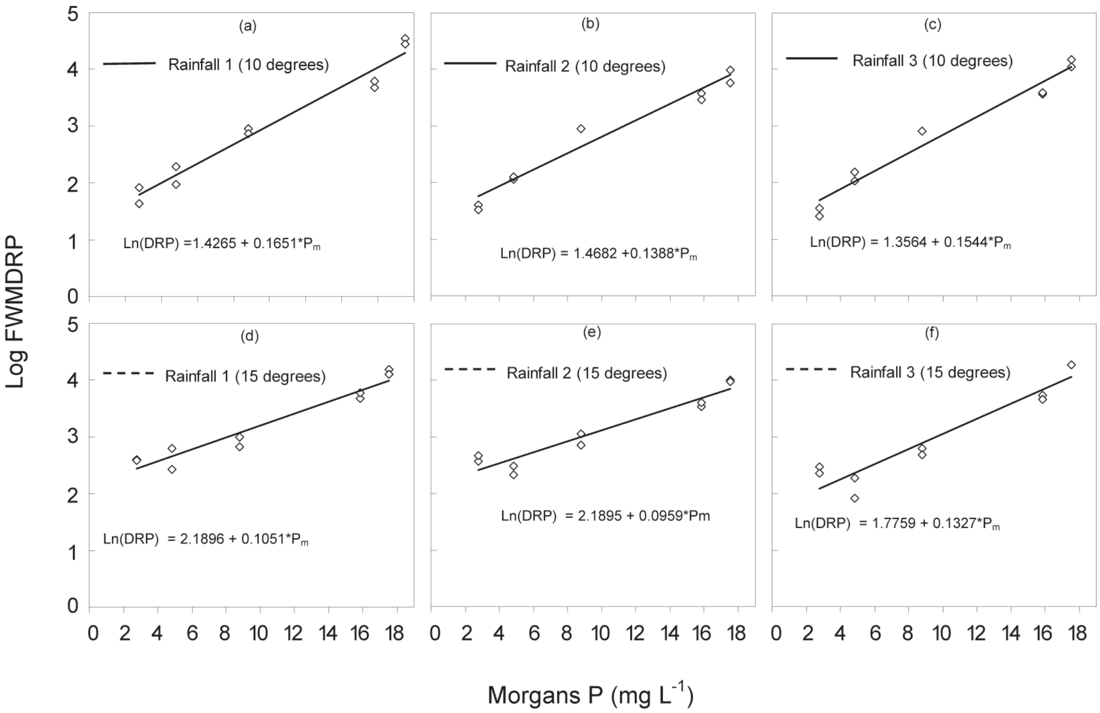

Fig. 3. Log flow-weighted mean dissolved reactive phosphorus (FWMDRP) against Morgan's P for selected tillage soils at 10 and 15 degree slopes under a 30 mm h^{-1} rainfall. Rainfall 1–first rainfall event; Rainfall 2–1 h after Rainfall 1; Rainfall 3–24 h after Rainfall 2.

and M3-P increase. For both 10- and 15-degree slopes, the first rainfall event had the highest FWMC of DRP in runoff from the five soils. The FWMC of DRP in surface runoff was lower during the second rainfall event, but was higher in the third. This increase may be attributed to more soluble P becoming available to runoff during a 24-h rainfall cessation than during a 1-h cessation. Sharpley (1980) found that when the time interval between rainfall events exceeds 1 d, the initial soluble P concentration in a runoff event increases.

Research by Foy et al. (2002) and Pote et al. (1999) found a positive relationship between P_m and DRP lost in surface runoff. A positive relationship between runoff DRP and soil WEP was also reported by Pote et al. (1996) using simulated rainfall on packed soil boxes. The WEP method closely mimics the interaction between rainwater and soil particles, and provides a good indication of DRP in runoff.

The 95% confidence bands (Fig. 4) indicate that provided the P_m does not exceed 9.5 mg L^{-1}, WEP does not exceed 4.4 mg kg^{-1} and M3-P does not exceed 67.2 mg kg^{-1}, for tillage soils, the concentration of DRP in runoff will be within the currently acceptable P range for surface water quality (< 30 µg L^{-1} molybdate reactive P). The finding for P_m in this study reinforces the statutory requirements of S.I. no. 101 of 2009, which prohibit fertilizer application to tillage soils with a P_m > 10 mg L^{-1} (Fig. 4a). In contrast, agri-environmental interpretation of M3-P in Delaware indicated that improved P management was necessary to reduce potential for nonpoint P pollution when M3-P > 150 mg kg^{-1} (Sims et al., 2002).

The predictions of the RDPRI may be affected by soil management decisions. Changes in soil management resulting in the deterioration or improvement of soil drainage may have the effect of reducing the predictive power of the RDPRI by increasing or decreasing, respectively, the overland flow volume. However, Kleinman et al. (2004) concluded that despite large differences in rainfall, hydrology, and erosion between field plots and packed boxes, both can be used to produce comparable P extraction coefficients for process-based models and P site assessment indices. Measures such as riparian buffer zones adjacent to tillage fields have the potential to alter the predictive power by reducing DRP loss in surface runoff.

Soil Parameters Affecting Nutrients and Sediment in Runoff

The GLMM (Table 2) indicated that the effect of soil type on the FWMC of DRP depended on both slope and time between rainfall events (p = 0.013). The effect of soil type depended only on surface slope for the FWMCs of SS (p = 0.044), TP (p = 0.014), and PP (p = 0.022) in surface runoff.

Soil extractable P can be measured in numerous ways in an attempt to predict DRP available to runoff. A stepwise regression selection procedure was used to identify the extractable P indicator best suited to predicting soluble P loss from Irish tillage soils. Measurement of soil WEP was selected as important when predicting DRP in runoff across all soils, slopes, and rainfall events. This is in agreement with other studies where WEP provided the strongest correlation with DRP concentrations in runoff when compared to other STP methods such as M3-P and Morgan's (Pote et al., 1996). Soil parameters also selected as important by stepwise regression to test for when predicting DRP in runoff were: STP, AgSt, pH, $Pcacl_2$, and

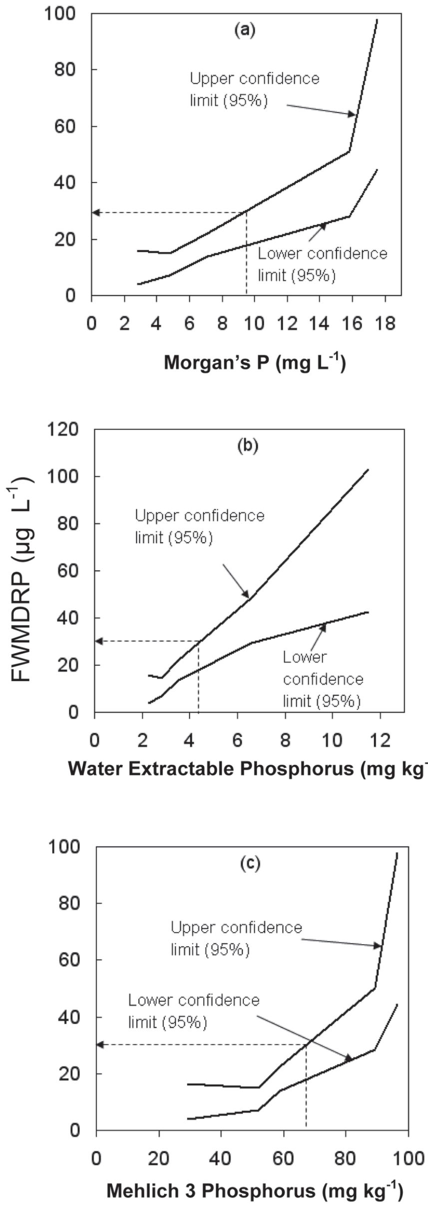

Fig. 4. Runoff dissolved P risk indicator using Morgan's P, water extractable P, and Mehlich 3-P for selected tillage soils at 10 and 15 degree slopes under a 30 mm h^{-1} rainfall. Rainfall 1–first rainfall event; Rainfall 2–1h after Rainfall 1; Rainfall 3–24 h after Rainfall 2.

clay. However, these were only selected for certain combinations of slope and rainfall event, and are less reliable indicators.

The effect of soil type on SS, PP, and TP loss to water differs depending on slope and, consequently, the stepwise procedure was performed separately for each slope. The soil parameters selected as important in predicting SS loss to water were: OM, AgSt, and clay. The $Psat_{ox}$ was selected as important when predicting PP and TP lost in runoff.

Conclusions

This study developed a RDPRI for Irish tillage soils–inclined at slopes of 10 and 15 degrees– when subjected to a rain-

Table 2. Overall ANOVA for responses from generalized linear mixed model (GLMM) analyses.

Source	DF	*F* value	*P* > *F*
Dissolved reactive P			
Soil type	4	768.58	< 0.0001
Slope	1	67.38	< 0.0001
Rainfall interval	2	12.94	< 0.0001
Soil × slope	4	240.97	< 0.0001
Soil × rainfall interval	8	3.54	0.005
Slope × rainfall interval	2	1.68	0.203
Soil × slope × rainfall interval	8	3.01	0.013
Total phosphorus			
Soil type	4	33.82	< 0.0001
Slope	1	10.62	0.002
Rainfall interval	2	32.70	< 0.0001
Soil × slope	4	3.49	0.014
Particulate phosphorus			
Soil type	4	27.51	< 0.0001
Slope	1	9.62	0.003
Rainfall interval	2	30.33	< 0.0001
Soil × slope	4	3.13	0.022
Suspended sediment			
Soil type	4	9.56	< 0.0001
Slope	1	14.87	0.001
Rainfall interval	2	9.65	0.001
Soil × slope	4	2.66	0.044

fall intensity of 30 mm h^{-1} at time intervals between rainfall events of 1 and 24 h. The main conclusions from this study are:

1. Provided the P_m does not exceed 9.5 mg L^{-1} for tillage soils, the concentration of DRP in runoff will be within the currently acceptable P range for surface water quality, thus reinforcing the statutory requirements of S.I. no. 101 of 2009 which prohibit fertilizer application to tillage soils with a P_m > 10 mg L^{-1}.
2. Tilled soils, subjected to the above conditions, may produce surface runoff P concentrations in excess of 30 µg L^{-1} (the value above which eutrophication of rivers is likely to occur) if their P_m, M3-P, and WEP concentrations exceed 9.5 mg L^{-1}, 67.2 mg kg^{-1}, and 4.4 mg kg^{-1}, respectively.
3. Stepwise regression suggested that soil WEP may be an important parameter to measure when attempting to predict DRP in runoff across all soils, slopes, and rainfall events investigated.

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