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Integrating Source and Transport Factors with Best Management Practices to Derive an Index for Assessing Phosphorus Mobilization Risks from Mauritius Sugarcane Fields

Tesha Mardamootoo[1], Christiaan Cornelius du Preez[2]*

[1]Mauritius Sugarcane Industry Research Institute, Redúit, Mauritius
[2]Department Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein, South Africa
Email: *dpreezcc@ufs.ac.za

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Abstract

Application of phosphorus (P) fertilisers to sugarcane fields in Mauritius increased almost four-fold per unit area over the past 60 years. Some of the applied P accumulated in the soils and can therefore be transported eventually to surface waters resulting in the eutrophication thereof. Precaution measures such as an appropriate P index as a management tool is required. Source factors (dissolved P, particulate P, P application rates, methods and timing), transport factors (soil erosion, runoff potential and precipitation factor) and a best management practices multiplier were integrated to derive an index for assessing risks of P mobilisation from the island's sugarcane fields. Farmers and their advisors can use the proposed P index during the planning process before sugarcane fields are planted and will be applicable for the whole crop cycle of 6 - 7 years if factors in the index do not change. The index can be also valuable in the selection of alternative management practices that could reduce the risks of P losses from sugarcane fields where the potential of P movement is initially high. Sensitivity analyses and edge-to-plot field tests showed that the P index needs further improvement, especially the estimation of soil erosion rates. The P index can, however, be applied by farmers and their advisors if they are well informed about the index's capability.

Keywords

Dissolved Phosphorus, Particulate Phosphorus, Phosphorus Fertiliser, Soil Erosion, Surface Runoff

1. Introduction

Phosphorus (P) is an essential macronutrient for plants and animals having, as reviewed by Higgs et al. (2000) an irreplaceable role in many physiological and biochemical processes. Soil has only a meagre supply of plant-available P and hence the application of either inorganic or organic P fertiliser to counter P supply as a limitation to crop growth is common to achieve profitable crop production (Havlin et al., 2014). Sugarcane production in Mauritius has been no exception as average P fertiliser rates have risen from 13.6 kg·ha^{-1} P_2O_5 in the 1950s to 49.6 kg·ha^{-1} P_2O_5 in 2009 (Mardamootoo et al., 2010).

As reviewed by Chen et al. (2008), an extensive use of P fertilisers invariably results in an accumulation of P in soil. Mardamootoo et al. (2012) reported that in 2005/2006 more than 50% of Mauritian sugarcane soils had a sound agronomic (>80 mg·kg^{-1} P extracted by 0.1 M H_2SO_4) but an unsafe environmental (>0.35 mg·kg^{-1} P extracted by 0.01 M $CaCl_2$) soil P status. These soil test P data when compared to those obtained in 1997/1998 indicate that current P management of sugarcane over a 7-year crop cycle is leading to an improvement in agronomic P status but to a deterioration in environmental P status (Mardamootoo et al., 2013). The environmental soil P status would continue to worsen in years to come with no precaution measures, predominantly in the two Latosolic soil groups with detrimental effects to surface water quality. Simulated rainfall studies by Mardamootoo et al. (2015) on 20 sugarcane fields with variable slopes and soils representing the agro-climatic regions of Mauritius, showed that the total P mobilised during runoff events was closely associated with suspended sediments present in runoff waters. Irrespective of soil, on average 89% of P losses occurred in particulate forms, also strongly linked to suspended sediments. The P-containing sediments in runoff waters may result in eutrophication of surface waters. Eutrophication of surface water leads to problems with its use for fisheries, recreation, industry and drinking due to increased growth of undesirable algae and aquatic weeds, causing oxygen shortages by their senescence and decomposition (Carpenter et al., 1998).

Above-mentioned prompted this investigation into a P index for the sugarcane fields of Mauritius. A P index is a field assessment tool specifically designed to enable farmers and their advisors to identify critical source areas like agricultural fields or parts of them that are most vulnerable to P loss in a watershed (Reid et al., 2012). Such an index integrates the major sources (e.g. soil P, fertiliser P) and transport (e.g. water erosion, deep percolation) factors controlling P movement in watersheds.

The P index is now widely adopted in the USA as well as in several countries in Europe, to estimate the risk of P loss from agricultural areas to surface waters (Berzina & Sudars, 2010). Currently in the USA, 47 states have implemented the P index as an assessment tool to identify critical source areas where remedial practices are to be targeted (Sharpley et al., 2011). In Europe, especially countries surrounding the Baltic Sea such as Denmark, Norway and Sweden have integrated P indices to improve the management of agricultural P. This popularity of P indices for routine applications by farmers and their advisors is attributed to that they are less complicated and data intensive than watershed models which are favoured by scientists (Gburek et al., 2006).

The P index originally developed by Lemunyon and Gilbert (1993) had the following goals:

- Assessing the risk of P transport from an agricultural field or part of it to a water body.
- Identifying the critical factors that influence P loss from an agricultural field or part of it.
- Helping to select management practices that would decrease P loss from an agricultural field or part of it.

Since its introduction by Lemunyon and Gilbert (1993), the P index has evolved considerably from being a critical source area identifier to serving now as a best management selector in inorganic and organic fertiliser scheduling tool of some states in the USA (Sharpley et al., 2012). As many as 34 site variables have to date been included in the different P indices developed across the USA and Europe (Nelson & Shober, 2012). The original P index comprised only of the characteristics soil erosion, runoff class, soil P test, P fertiliser type and application method, and the five value categories of none, low, medium, high and very high (Lemunyon & Gilbert, 1993).

The challenge for P index developers is to determine the soil, landscape and climate conditions within their jurisdiction components to be used and the relative weighting of each to reflect the actual risk of P movement into surface water (Reid et al., 2012). Different P indices have therefore developed to reflect regional-specific variations in soil type, land management, climate conditions, physiographical features, hydrological controls, fertiliser management strategies and accepted policies (Sharpley et al., 2012).

We aimed with this investigation to derive a P index for Mauritian sugarcane fields by integrating source and transport factors with best management practices. The ideal was that this P index must have an end-use practicability for P management on sugarcane fields. Sugarcane producers and water users of the island can benefit from such a P index that is able to assist in identifying agricultural fields or parts of them having soils with high P status where remedial actions are required to reduce P pollution of surface water.

In this paper, first an outline is given of the steps followed to derive the P index. Second, the calculation and risk assessment of the P index are dealt with. Third, the P index is evaluated using sensitivity analyses and edge-of-plot field tests.

2. Derivation of Phosphorus Index

The proposed P index integrates source factors (amount of P in soils available for transport), transport factors (hydrological processes causing P losses from fields) and best management practices able of reducing P mobilisation. Due to staff shortages, measurements were made only at 20 of the 30 field sites initially identified for the derivation of the P index (**Figure 1**). These 20 field sites are representative of the five main soil groups under sugarcane production in Mauritius. The five soil groups are: Low Humic Latosol, Humic Latosol, Humic Ferruginous Latosol, Latosolic Reddish Prairie and Latosolic Brown Forest.

2.1. Source Factors

Five source variables were identify for inclusion in the P index as given in **Table 1**. The inclusion of each is concisely justified.

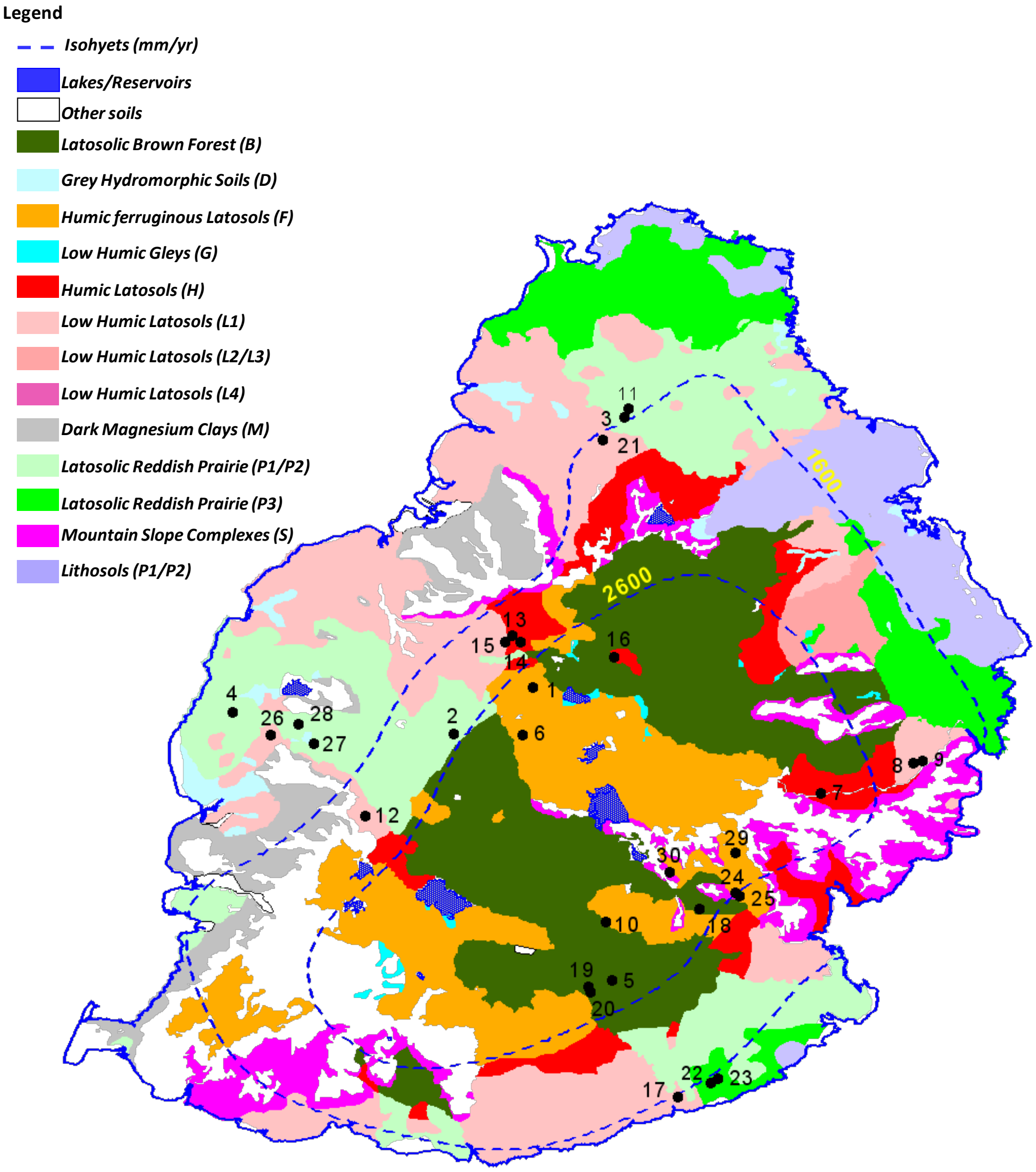

Figure 1. The different soil groups in Mauritius according to Parish and Feillafé (1965) and the location of identified study sites. Measurements were made at only 20 of the 30 study sites initially identified due to staff shortages.

Table 1. Phosphorus loss potential in Mauritius due to source factors.

Proposed P source factors	Proposed P loss category	Proposed loss rating value
Dissolved P		$0.01207\ e^{0.00925 \times \text{Soil test P (mg·P·kg}^{-1})}$
Particulate P		$5.5 \times$ erosion (t·ha^{-1}·yr^{-1})
P application		kg P_2O_5 applied ha^{-1}·yr^{-1}
Application method	Buried (depth > 200 mm) in furrows	0.2
	Buried (depth < 200 mm) in furrows	0.4
	Surface application with cane trash	0.6
	Surface application on bare soil	1.0
Application timing	September to December	0.2
	April to August	0.3
	January to March	0.5

P application rating = (P application rate × method × timing); source potential = dissolved P loss rating + particulate P loss rating + P application rating.

2.1.1. Dissolved Phosphorus

Studies by Sharpley (1985) showed that the loss of dissolved P in surface runoff is highly dependent on the extractable P content of soil to 50 mm depth. In Mauritius, soil testing to 450 mm depth for fertiliser recommendations is every time done when the sugarcane fields after a crop cycle of 6 - 7 years are replanted (Mardamootoo et al., 2012). Based on 0.1 M H_2SO_4 extraction of soil P, no fertilisers is recommended for soils having a P status greater than 80 mg·kg^{-1} while soils having a P status above 160 mg·kg^{-1} increase P concentration of runoff waters significantly, causing impairment of surface water quality (Mardamootoo et al., 2013). For practical reasons, the relationship between agronomic soil test P concentrations and orthophosphate-P concentrations in runoff (**Figure 2**) is therefore for the estimation of dissolved P used (**Table 1**). This will not incur additional workload and costs associated with different soil sampling depths (Heathwaite et al., 2003). Nonetheless, Withers et al. (2007) cautioned that agronomic soil P status to 450 mm depth may result in an underestimation of potential P loss risks from the upper 50 mm soil in runoff waters.

2.1.2. Particulate Phosphorus

Rainfall simulation studies in Mauritius showed that particulate P accounts on average 89% of total P in runoff waters (Mardamootoo et al., 2015). Contrarily to dissolved P losses, is the prediction of particulate P losses inaccurate from soil P tests and best estimated from erosion rates (Ekholm et al., 2005). In the proposed P index, particulate P is the slope (**Table 1**) of the linear relationship between amount of soil loss and particulate-P transported in runoff waters (**Figure 3**), corrected from kg·ha^{-1} to t·ha^{-1}.

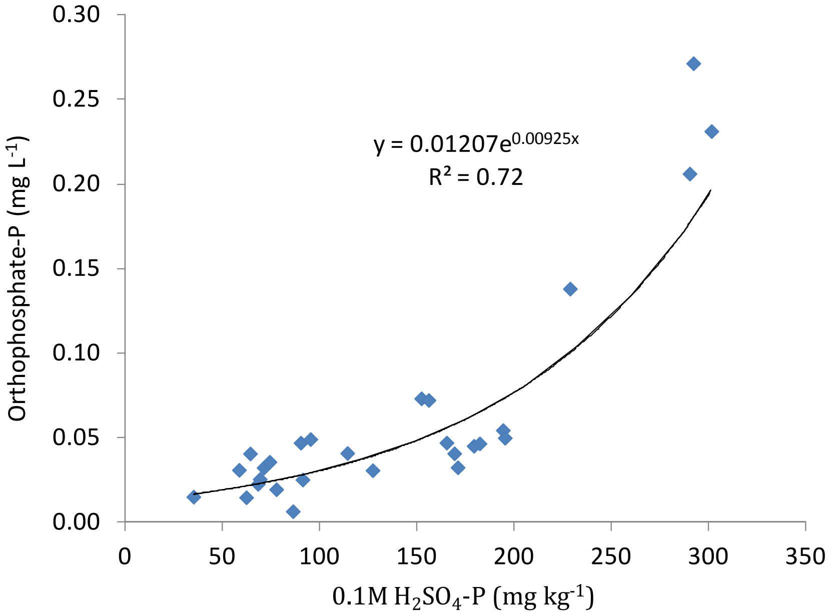

Figure 2. Relationship between soil test P (i.e. the 0.1 M H_2SO_4-P) and the orthophosphate-P concentrations in runoff.

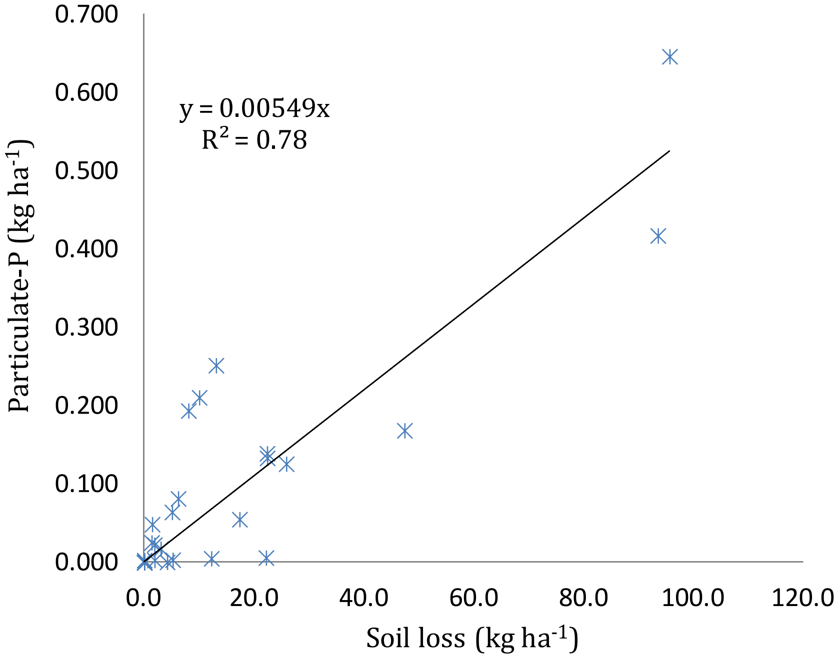

Figure 3. Relationship between amount of soil loss and particulate P transported in runoff waters.

2.1.3. Phosphorus Application

The P fertiliser recommendation guidelines of Cavalot et al. (1988) for sugarcane production in Mauritius were for the P index adopted (**Table 2**). Fertiliser P is not recommend to sugarcane soils with more than 80 mg P kg^{-1} extracted by 0.1 M H_2SO_4. For sugarcane cultivation, P fertilisation at planting is an important practice as all P for the whole crop cycle of 6 - 7 years is applied. In addition to

Table 2. Phosphorus fertiliser recommendations to sugarcane in Mauritius based on soil P test values (compiled from Cavalot et al., 1988).

Soil test value (0.1 M H_2SO_4-P, mg·kg^{-1})	kg P_2O_5 ha^{-1} to apply (to raise soil P to 80 mg·kg^{-1})
30	600
35	525
40	475
45	425
50	375
55	325
60	275
65	200
70	125
75	50
80	0

inorganic fertilisers, it is common practice to apply scum in the furrows before planting at a minimum rate of 12 t·ha^{-1} for a homogenous coverage in the furrow (STASM, 2003).

The application method comprised of four suggested categories, namely buried in furrows at a depth greater than 200 mm, buried in furrows at a depth less than 200 mm, surface applied with cane trash, and surface applied on bare soil. The risk associated with P losses with the placement of fertiliser at plantation in the furrow, compared to surface application is reflect by the P loss rating values in **Table 1**. This concurs with the findings of Mueller et al. (1984).

Timing of P application to soils relative to when runoff occurs is a key consideration for preventing incidental P losses. In tropical environments such as Mauritius, one of the most critical drivers of offsite movement of P is the onset of seasonal rainfall (Sallaway et al., 2001). The potential for P loss is greater immediately following P application and then declines over time, as the added P gradually interacts with soils into increasingly recalcitrant forms (Sharpley et al., 2002).

Mauritius is categorised by Halais and Davy (1969) into three agro-climatic regions, namely sub-humid (<1500 mm annually), humid (1500 to 2500 mm annually) and super-humid (>2500 mm annually). The mean monthly rainfall distribution for the three agro-climatic regions from 2004 to 2013 shows that the highest rainfall period is from January to March, followed by April to August and September to December (**Figure 4**). In consequence, the highest risks of P losses will occur during the months of January to March, especially if P fertilisers are applied that period. The relative P loss rating values in **Table 1** are the percentage annual rainfall during each period (**Table 3**).

The P application rating is obtained by multiplying the P application rate by

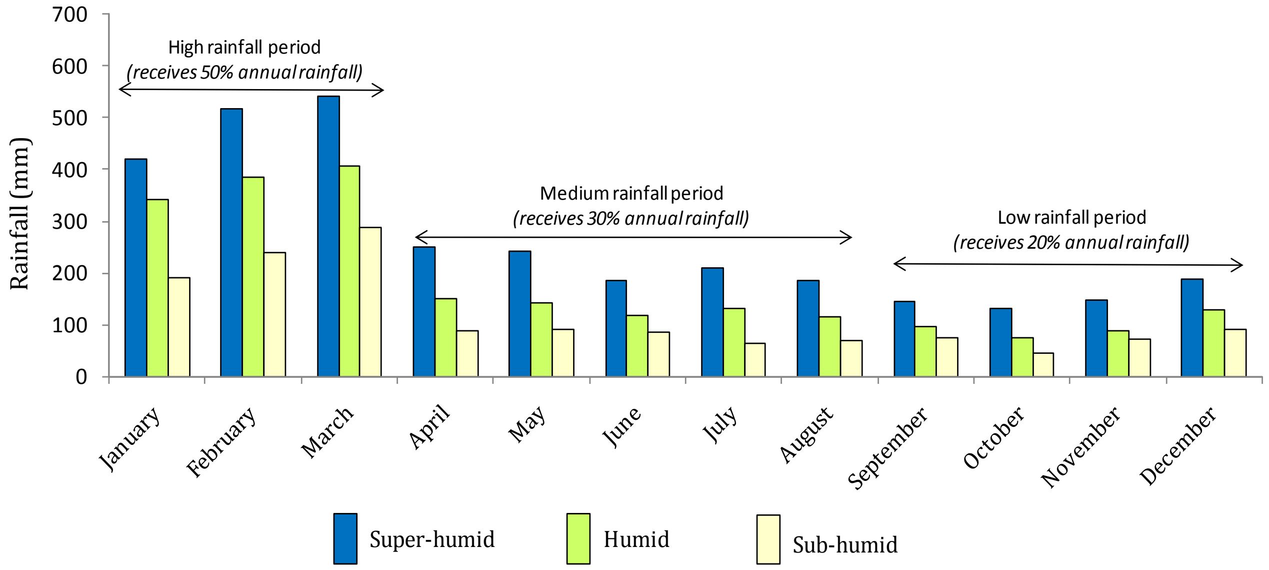

Figure 4. Mean monthly rainfall distribution over the three agro-climatic regions of Mauritius from 2004 to 2013.

Table 3. Rainfall distribution as a percentage of annual rainfall during three periods for the agro-climatic regions of Mauritius, assigned a loss rating value for P application timing.

Period	Percentage of annual precipitation				Loss rating value
	Super-humid	Humid	Sub-humid	Mean	
January to March	47	52	52	50	0.5
April to August	34	30	28	31	0.3
September to December	19	18	20	19	0.2

the loss rating values for application method and application timing, while the overall source potential is the sum of the dissolved P rating, particulate P loss rating and P application rating as indicated in Table 1.

2.2. Transport Factors

Three transport variables were included in the proposed P index for Mauritius, namely soil erosion, runoff potential and a precipitation factor (Table 4).

2.2.1. Soil Erosion

The simulated rainfall-runoff studies at the 20 sugarcane fields of Mauritius showed that soil erosion (from 22.1 m long by 10 m wide plots) represents a significant mechanism for P transport at planting of sugarcane, the time in the crop cycle when fields are ploughed recently and there is no plant cover (Mardamootoo et al., 2015). As in most existing P indices, erosion prediction models such as the Revised Universal Soil Loss Equation (RUSLE) described by Hudson (1992) is been utilized to estimate average annual erosion. In the proposed P index for Mauritius, the P annual erosion was estimate by RUSLE2 (modified by Foster et al., 2003) as follows:

Table 4. Phosphorus loss potential in Mauritius due to transport factors.

Proposed P transport factors	Category	Proposed loss rating value
Soil erosion		$t \cdot ha^{-1} \cdot yr^{-1}$
Runoff potential	Very Low	0.2
	Low	0.4
	Medium	0.6
	High	0.8
	Very high	1.0
Precipitation factor	Sub-humid region	0.64
	Humid region	1.00
	Super-humid region	1.46

TRANSPORT POTENTIAL = (Erosion + Runoff potential) × Precipitation factor.

$$A = R \times K \times L \times S \times C \times P \tag{1}$$

- A is the estimated soil loss per unit area averaged over time and space for a given sugarcane field and is expressed in $t \cdot ha^{-1} \cdot yr^{-1}$.
- R is the rainfall-runoff erosivity factor accounting for the rainfall characteristics and the runoff characteristics generated by the rainfall. Studies undertaken in Mauritius by Seeruttun et al. (2006) suggested that a mean value of 300 is suitable for R to predict soil losses.
- K is the soil erodibility factor accounting for soil properties that influence soil loss and is thus soil specific. Seeruttun et al. (2006) suggested factors of 0.14, 0.05, 0.08 and 0.01 for soil loss prediction in the Low Humic Latosol (LHL), Humic Ferruginous Latosol (HFL), Latosolic Brown Forest (LBF) and Humic Latosol (HL) soil groups of Mauritius, respectively. These factors were established on soil erosion plots (22.1 m long by 10 m wide) under natural rainfall over a 4-year period. For the Latosolic Reddish Prairie soils (LRP), a K value of 0.01 was assume since those soils usually have high infiltration rates due to the presence of non-weathered basaltic gravel (Parish & Feillafé, 1965).
- L is the length factor and this ratio compares the soil loss from a field of specified length of 22.1 m.
- S is the slope steepness factor that is determined on the field for a given slope length.
- C is the cover or cropping-management factor and is use to reflect the effect of cropping and management practices on erosion rates. In Mauritius, the C factor for sugarcane is considered as 0.07 (Seeruttun et al., 2006).
- P is the conservation support practice that accounts for those practices (e.g. contouring, strip-cropping or terracing) that affect soil erosion by modifying the flow pattern, grade or direction of surface runoff. Values for the P factor were obtain from the Arkansas nutrient management planner's guide (Daniels et al., 2005) and are a function of rainfall energy and intensity factor (EI). The EI values of 100, 110 and 130 were assume for the sub-humid, hu-

mid and super-humid regions, respectively.

Soil erosion estimates were for the different combinations of slopes, soil types and agro-climatic regions calculated but differences between the three agro-climatic regions for specific slope and soil type combinations were little. Only the average soil erosion estimates and coinciding standard errors across the three agro-climatic regions for slope and soil type combinations are in **Table 5** presented due limited space. However, estimates of soil erosion for all combinations of slopes, soil types and agro-climatic regions were use in the developing of the P index. Furthermore, it is noteworthy that the average soil erosion estimates for the Humic Latosols and Latosolic Reddish Prairie soil groups were the same.

2.2.2. Surface Runoff

Surface runoff classes, based on soil type and field slope, are included in the P index. For this the ratios of runoff to rainfall were calculate from the rainfall simulation tests done in the sugarcane fields and these ratios were utilise to determine the permeability of the five main soil groups in Mauritius (**Table 6**).

Table 5. Estimated annual average soil loss as a function of soil type and slope for the three agro-climatic regions of Mauritius.

Slope (%)	Estimated annual soil loss ($t \cdot ha^{-1} \cdot yr^{-1}$)				
	LHL	LBF	HFL	HL	LRP
1	1.22 ± 0.07	0.70 ± 0.04	0.43 ± 0.03	0.09 ± 0.01	0.09 ± 0.01
2	2.03 ± 0.51	1.33 ± 0.12	0.83 ± 0.08	0.17 ± 0.02	0.17 ± 0.02
3	3.45 ± 0.36	1.97 ± 0.02	1.23 ± 0.13	0.25 ± 0.02	0.25 ± 0.02
4	4.57 ± 0.49	2.61 ± 0.28	1.63 ± 0.18	0.33 ± 0.04	0.33 ± 0.04
5	5.71 ± 0.61	3.26 ± 0.35	2.04 ± 0.22	0.41 ± 0.05	0.41 ± 0.05
6	6.93 ± 0.69	3.96 ± 0.39	2.48 ± 0.25	0.49 ± 0.05	0.49 ± 0.05
7	8.18 ± 0.75	4.67 ± 0.43	2.92 ± 0.27	0.59 ± 0.06	0.59 ± 0.06
8	9.52 ± 0.78	5.44 ± 0.45	3.40 ± 0.28	0.68 ± 0.06	0.68 ± 0.06
9	10.91 ± 0.74	6.23 ± 0.42	3.90 ± 0.26	0.78 ± 0.05	0.78 ± 0.05
10	12.38 ± 0.68	7.08 ± 0.39	4.42 ± 0.24	0.89 ± 0.05	0.89 ± 0.05
11	13.86 ± 0.58	7.92 ± 0.32	4.95 ± 0.21	0.99 ± 0.04	0.99 ± 0.04
12	15.44 ± 0.31	8.82 ± 0.18	5.52 ± 0.11	1.11 ± 0.02	1.11 ± 0.02
13	16.89 ± 0.17	9.65 ± 0.10	6.03 ± 0.06	1.21 ± 0.01	1.21 ± 0.01
14	18.38 ± 0.00	10.50 ± 0.00	6.56 ± 0.00	1.31 ± 0.00	1.31 ± 0.00
15	19.69 ± 0.00	11.25 ± 0.00	7.03 ± 0.00	1.41 ± 0.00	1.41 ± 0.00
16	21.00 ± 0.00	12.00 ± 0.00	7.50 ± 0.00	1.50 ± 0.00	1.50 ± 0.00
17	22.31 ± 0.00	12.75 ± 0.00	7.97 ± 0.00	1.59 ± 0.00	1.59 ± 0.00
18	23.63 ± 0.00	13.50 ± 0.00	8.44 ± 0.00	1.69 ± 0.00	1.69 ± 0.00
19	24.94 ± 0.00	14.25 ± 0.00	8.91 ± 0.00	1.78 ± 0.00	1.78 ± 0.00
20	26.25 ± 0.00	15.00 ± 0.00	9.38 ± 0.00	1.88 ± 0.00	1.88 ± 0.00

LHL = Low Humic Latosol, LBF = Latosol Brown Forest, HFL = Humic Ferruginous Latosol, HL = Humic Latosol, LRP = Latosolic Reddish Prairie.

Table 6. Soil permeability at three different slope categories for the five main soils of Mauritius.

Soil type	Slope (%)	Permeability (mm·hr^{-1})	
		Range	Mean ± SE
Low Humic Latosol (LHL)	0 - 8	131 - 148	139 ± 4
	8 - 13	84 - 146	119 ± 13
	13 - 20	99 - 145	116 ± 10
Humic Latosol (HL)	0 - 8	64 - 149	123 ± 30
	8 - 13	102 - 121	110 ± 6
	13 - 20	66 - 128	88 ± 20
Humic Ferruginous Latosol (HFL)	0 - 8	129 - (>150)[a]	-
	8 - 13	97 - 124	110 ± 6
	13 - 20	114 - 121	116 ± 2
Latosolic Reddish Prairie (LRP)	0 - 8	85 - (>150)[a]	-
	8 - 13	94 - 141	127 ± 8
	13 - 20	101 - 116	122 ± 10
Latosolic Brown Forest (LBF)	0 - 8	125 - 139	125 ± 10
	8 - 13	124 - 148	132 ± 8
	13 - 20	127 - 147	135 ± 6

[a] Soil permeability greater than the amount of simulated rainfall applied.

Based on these results, the soil groups were group into three permeability classes of slow, moderate and rapid (Table 7). A similar approach to that of the Maryland P index (Anon, 2008) was adopt to estimate the surface runoff potential in the P index for Mauritius and takes into account soil permeability and slope categories, where low permeability coupled with steep slopes represents the highest risk to surface runoff and P mobilisation.

2.2.3. Precipitation Factor

The mean annual rainfall of Mauritius changes abruptly from 800 mm on the west coast of the island to over 4000 mm in the central plateau over a distance of only 20 km, and the risk of surface runoff and soil erosion is expect to increase accordingly. It was therefore imperative to include a precipitation factor in the P index. The precipitation factor for the three agro-climatic regions was obtained by normalising the annual rainfall to that occurring in the humid region. The resulting precipitation factors are 0.64 for the sub-humid region, 1.00 for the humid region and 1.46 for the super-humid region (Table 8).

2.3. Best Management Practices Multiplier

The adoption of best management practices (BMPs) in reducing P losses is accommodate by the inclusion of a BMPs multiplier, an approach similar to the one adopted in the Arkansas P index (Sharpley et al., 2010). The multiplier associated

Table 7. Surface runoff potential in Mauritius as a function of soil type and slope.

Soil type	LRP	HFL	LBF	LHL	HL
Relative permeability class	Rapid	Rapid	Moderate	Moderate	Slow
Slope (%)	Relative runoff risk				
0 - 8	VL	VL	L	L	M
8 - 13	L	L	M	M	H
13 - 20	M	M	H	H	VH
>20	H	H	VH	VH	VH

VL: Very low, L: Low, M: Medium, H: High, VH: Very High.

Table 8. Precipitation factor for the agro-climatic regions of Mauritius.

Agro-climatic zone	Annual precipitation, mm	Precipitation factor
Sub-humid	1390	0.64
Humid	2170	1.00
Super-humid	3160	1.46

with each BMP is calculate as one minus the effectiveness of the BMP implemented and the multiplier for all the BMPs implemented will then be computed as follows:

$$\text{BMPs multiplier} = \left(1-\text{Effectiveness}_1\right)\times\left(1-\text{Effectiveness}_2\right)\times\left(1-\text{Effectiveness}_n\right) \quad (2)$$

If no additional BMPs are implemented, the BMPs multiplier is equal to 1 and if BMPs are adopted, then the BMP multiplier will have a value less than 1. In addition to the management practices considered in the source and transport components of the P index, other possible BMPs and their effectiveness in decreasing runoff P losses are in Table 9 presented.

3. Phosphorus Index Calculation and Risk Interpretation

The overall P index rating for a given sugarcane field or part of it is calculated by multiplying the source potential, transport potential and BMPs multiplier with one another as outlined below:

$$\text{Overall P index rating} = \text{Source potential}\times\text{Transport potential}\times\text{BMPs multiplier} \quad (3)$$

Once the P index value is calculated, sugarcane fields are assign a P loss risk of either low, medium, high or very high with each of the four classes being associated with an interpretation and guided management practice as shown in Table 10. Recommendation range from cautions regarding build-up of soil P levels for the low risk class to no additional P application until soil P levels declined to acceptable levels for the very high class.

4. Evaluation of Phosphorus Index

For the evaluation of the proposed P index, sensitivity analyses and edge-of-plot field tests were carry out and the outcomes of each are dealing with below.

Table 9. Credit given for potential best management practices (BMPs) for use in the phosphorus index to assess P losses from sugarcane fields in Mauritius (adapted from Sharpley et al., 2010).

Best management practice (BMP)	Credit (%)
Diversion	5
Pond	20
Field border	10
Herbaceous buffer	20
Forest buffer	20
Filter strip	20
Grassed waterway	10
Structure for runoff water control	30
Terrace	10
Wetland creation	20

Table 10. Interpretation and recommendations for P indices of sugarcane fields in Mauritius (adapted from Sharpley et al., 2001a; Weld et al., 2001; DeLaune et al., 2006).

P index value	P loss risk	General interpretation and recommendations
<33	Low	*Low potential for P loss*. If current farming practices are maintain, there is a low risk of adverse impacts on surface waters.
33 to 65	Medium	*Moderate potential for P loss*. The chance for adverse impacts on surface waters exists, and remediation measures should be introduce to minimise P loss. Use of the P index to identify specific field areas that could represent long-term concerns and the implementation of BMPs are to be consider in those areas.
66 to 100	High	*High potential for P loss* and adverse impact on surface waters. To determine using the P index if one factor is disproportionally affecting risk of P losses. Inclusion of an appropriate BMP and/or reducing P application to bring P loss risk to medium (<65) is warranted. A conservation P management plan is required with the long-term goal of shifting the P loss risk to the medium or lower category.
>100	Very High	*Very high potential for P loss* and adverse impact on surface waters. The adoption of BMPs to decrease this value below the very high category in the short term and a conservation management plan that would reduce the P loss risk to a lower risk category, with the long-term goal of having a P index in the medium or lower category.

4.1. Sensitivity Analyses

As suggested by Brandt and Elliot (2005), we ran sensitivity analyses to evaluate the behaviour and assess which factors of the P index have the greatest influence on the P index ratings estimated with it. This entailed the creating of a baseline scenario with typical field characteristics and varying each P index variable while keeping the others constant. This approach isolate the effect of each component on the P index rating.

The P index correctly reflects that with increasing extractable soil P levels, the risks of P losses during runoff events increases (**Figure 5(a)**). Sensitivity analyses revealed further that the P index ratings increase with increasing P application rates. Unlike application rate, a continuous variable in the P index, application method and timing have been included as discrete variables with clear-cut distinction among different P loss categories (**Table 1**). **Figure 5(b)** shows that the

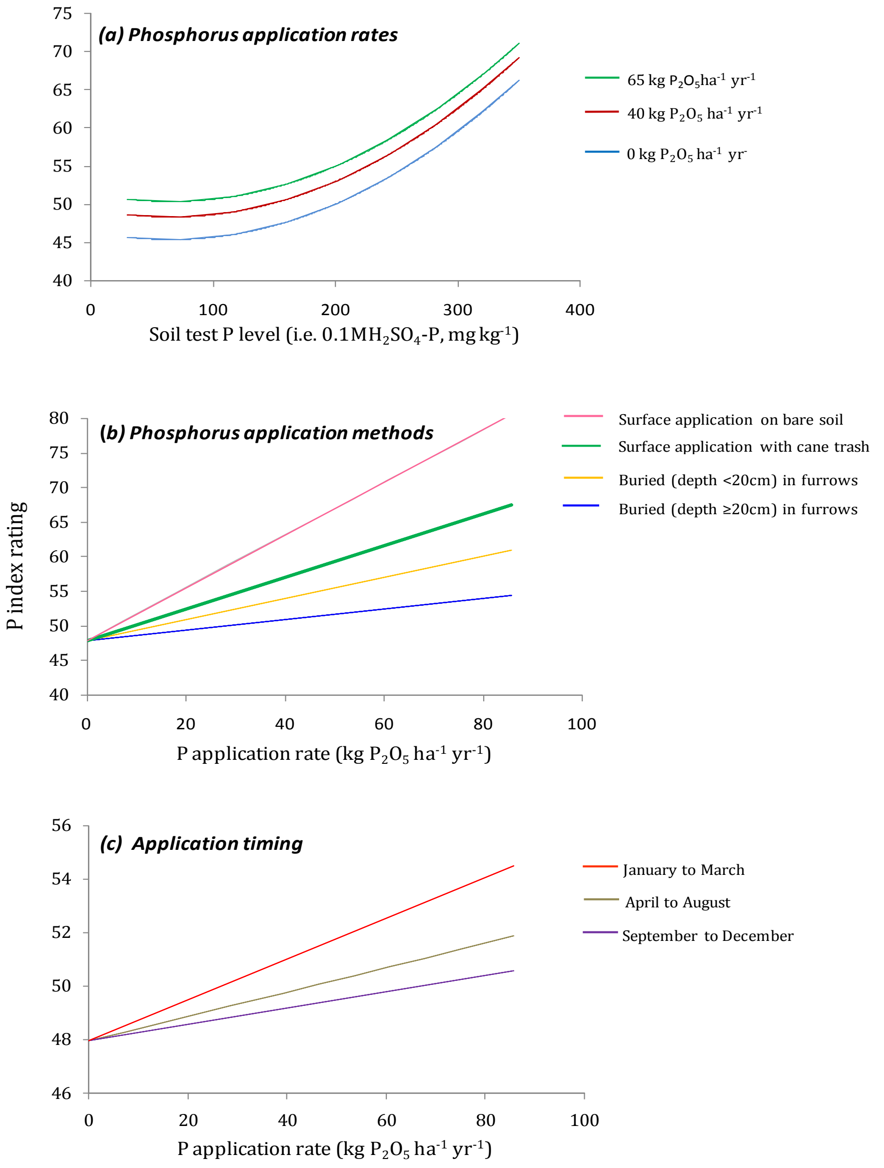

Figure 5. Sensitivity of the P index to (a) phosphorus application rates, (b) phosphorus application methods, and (c) phosphorus application timing. (Baseline conditions unless indicated otherwise in figure: 160 mg·kg^{-1} 0.1M H_2SO_4-P, 10.50 t·ha^{-1}·yr^{-1} erosion rate, 8% field slope, fertilisers applied in furrows at a depth of 20cm in February).

rate of change in the P index rating is the highest when P sources are surface applied on bare soil and is the lowest when buried in furrows at a depth greater than 200 mm. From an environmental point of view, is therefore advisable that P sources are from September to December applied when risks of P loss is lowest (**Figure 5(c)**).

Despite that transport variables are often inter-related, sensitivity analyses indicate that the P index respond to changes in slopes across the five main soil groups under sugarcane in Mauritius (**Figure 6**). Irrespective of soil type, the P index rating increases as the field slopes become steeper. This increase in the P index rating is due to a higher vulnerability of the fields to surface runoff and soil erosion owing to increasing field slopes. The highest erosion rate realised for the Low Humic Latosol, followed by the Latosolic Brown Forest, Humic Ferruginous Latosol, Humic Latosol and Latosolic Reddish Prairie soils. Hence, soil conservation measures should generally be target to sugarcane fields on the Low Humic Latosols especially those located on steep slopes. Nonetheless, a small change in field slope results in a relatively large increase in the P index rating especially for the Low Humic Latosols, suggesting that the erosion factor is a highly weighted variable in the P index. Future research efforts should be oriented therefore towards improving the accuracy of soil erosion rates estimates.

At the studied sites, a simulated rainfall intensity of 100 mm·h^{-1} lasting for 30 min resulted in P mobilization of 2 to 163 g P ha^{-1} during erosion (Mardamootoo et al., 2015). The total P in runoff waters including sediments ranged between 0.2 and 1346 g·ha^{-1}. This suggested that total P mobilised during runoff was mainly associated with suspended sediments therein. Soil detachment during

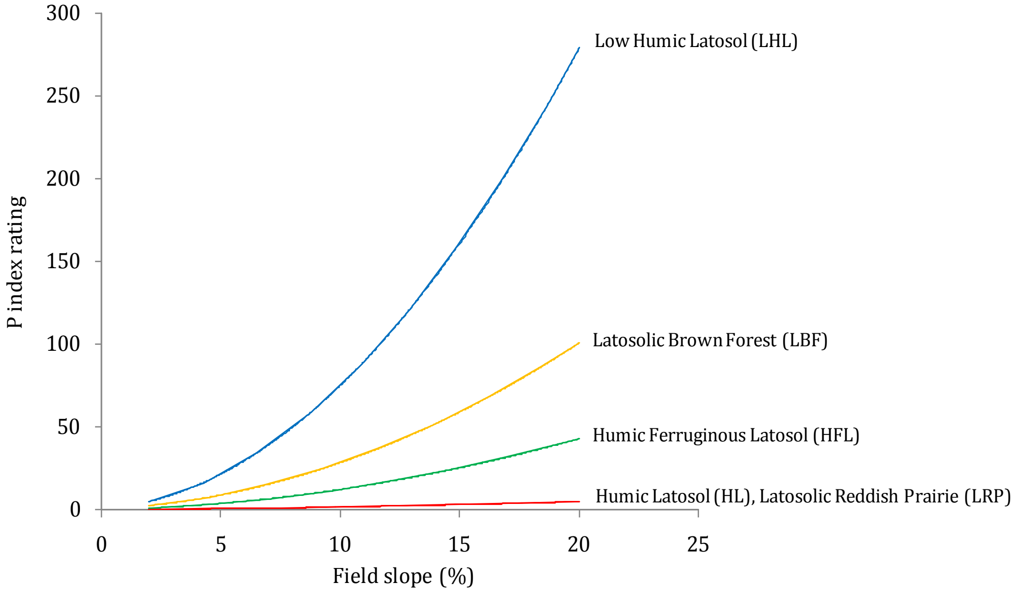

Figure 6. Sensitivity of the transport component of the P index across different soil types with varying field slopes. (Baseline conditions: 160 mg·kg^{-1} 0.1M H_2SO_4-P, fertilisers applied at a rate of 45 mg·kg^{-1} P_2O_5 in furrows at a depth of 200 mm in February).

erosion represent therefore a significant mechanism for P loss during rainfall events. Irrespective of soil type, P losses occurred largely in particulate forms which were in turn strongly linked to suspended sediment in runoff waters, confirming that suspended soil particles control runoff particulate P.

4.2. Edge-of-Plot Field Tests

Edge-of-plot field simulated rainfall studies were carried out at 10 representative sugarcane fields with varying slopes (0 - 8, 8 - 13 and 13% - 20%) and rainfall intensities (50, 100 and 150 mm·h^{-1}) to measure total P concentrations in the runoff waters. The measured total P concentrations in the runoff waters from the 2.1 m long by 0.75 m wide plots were compare with the corresponding P index ratings of the respective field sites.

The total P concentrations in the runoff waters were poorly correlated (r^2 = 0.15) to soil P test levels determined by the 0.1 M H_2SO_4 extraction (**Figure 7**). This trend is similar to that observed in the simulated rainfall-runoff studies done for the development of the P index. A drawback of the evaluation of the P index at runoff plot scales is that factors operating at larger scales (mostly transport factors) are not taken into account (Buczko & Kuchenbuch, 2007). Indeed this could explain the poor relationship between P index ratings and total P concentrations in runoff waters following simulated rainfall (**Figure 8(a)**). This relationship improved when instead of the overall P index rating, the source potential rating was correlate with total P concentration in runoff (**Figure 8(b)**), thus showing that transport factors cannot be adequately validated using small runoff plots. Therefore, in addition to this plot-scale assessment of the P index, a watershed-scale validation is also required to complement the edge-of-plot field results (Sharpley et al., 2001b). Until more validation data is available, it is of critical

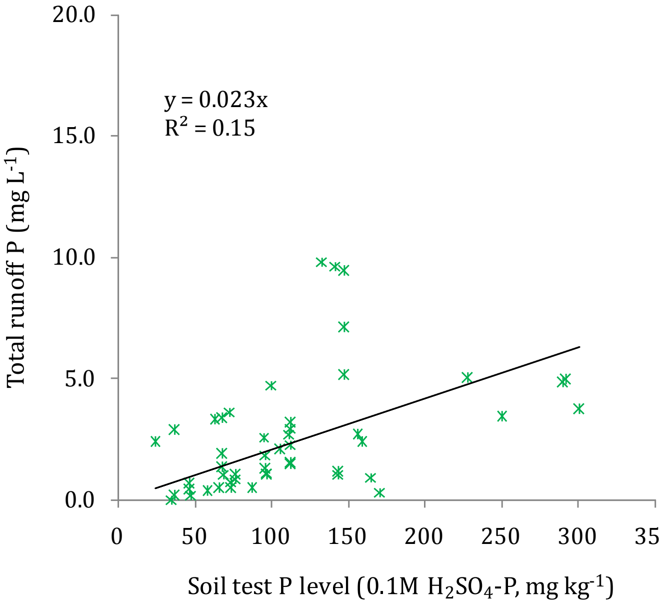

Figure 7. Relationship between soil test P level and total runoff P concentrations under simulated rainfall conducted on runoff plots of 2.1 m long by 0.75 m wide.

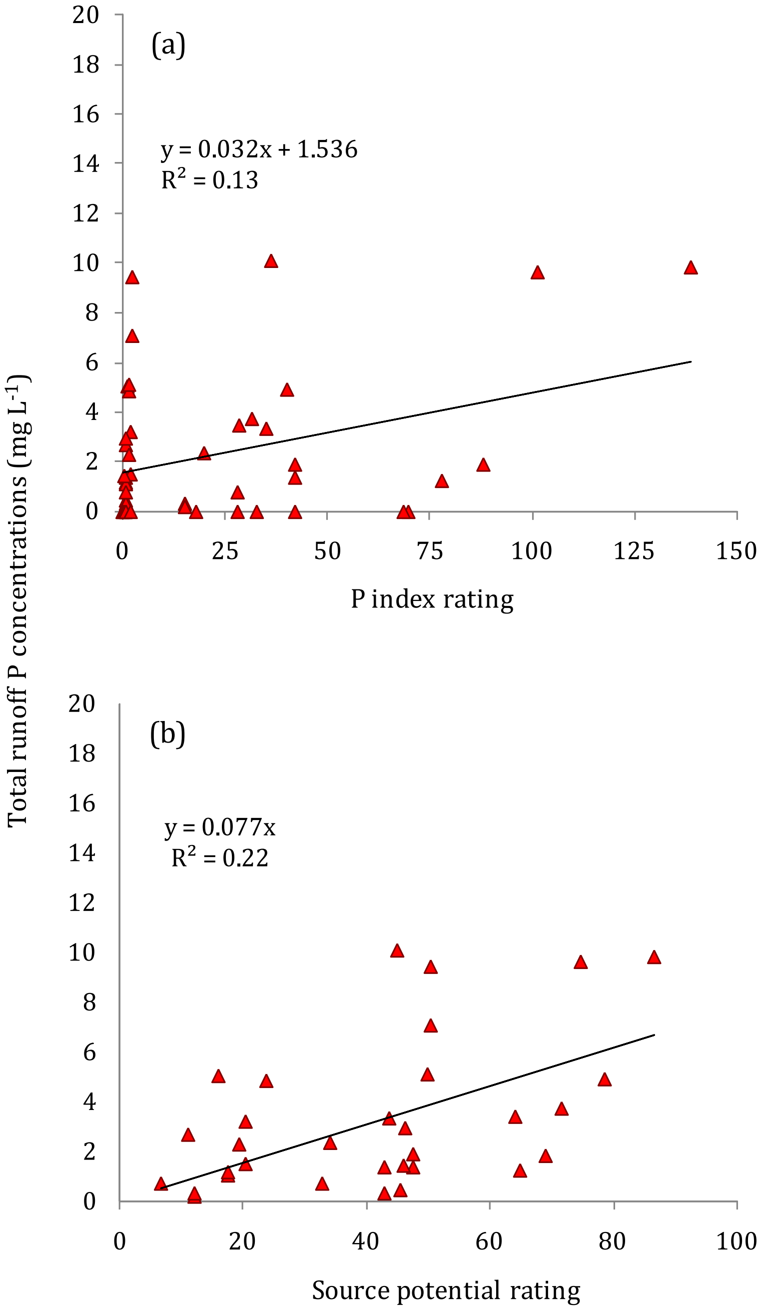

Figure 8. Relationship between (a) P index ratings (b) source potential ratings and total runoff P concentrations following 30 minutes simulated rainfall (50, 100 and 150 mm·hr^{-1}) over runoff plots of 2.1 m long by 0.75 m wide.

importance that along with the calculated field P index ratings, clear definition of what the risk assessment tool is useful for or not is convey to farmers and their advisors.

5. Conclusion

The P index proposed to evaluate the risk of P losses from sugarcane fields in Mauritius is a qualitative assessment tool ranking field site's vulnerability to P loss. Five source factors (dissolved P, particulate P, P application rate, method and timing), three transport factors (soil erosion, runoff potential and precipitation factor) and a best management practices multiplier were included in the P index. The P index could be part of the planning process before the sugarcane fields are planted and will be applicable for the whole sugarcane crop cycle of 6-7 years as long as all other factors in the P index remain the same for the period. When management changes occur during the crop cycle, it will be necessary to evaluate if these changes have an influence on the P index and risk of P losses. Moreover, the P index would help during the planning process to select alternative management practices that could reduce the risk of P losses from sugarcane fields where the potential of P movement is initially high. The evaluation and validation of the proposed P index is necessary to ensure an accurate and efficient nutrient management tool for farmers and their advisors. However, sensitivity analyses show that soil erosion appears to be a highly weighted factor in the P index whereof the estimation requires improvement. The edge-of-plot field tests indicate further that small runoff plots are inadequate to evaluate transport factors satisfactory. Nonetheless, farmers and their advisors can apply the proposed P index as long as they are aware of its shortcomings.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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