# Remaining phosphorus content to determine phosphorus availability of the soils in Rio Grande do Sul

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Abstract – The objective of this work was to evaluate remaining P compared with soil clay content as a P buffer index to classify P extracted by the Mehlich-1 (M1) and Mehlich-3 (M3) methods in soils from the state of Rio Grande do Sul, Brazil. The experiment was carried out in a completely randomized design with five $P_2O_5$ rates (0, 50, 100, 200, and 400 mg kg$^{-1}$) and two sucessive corn crops, and three replicates, in 20 representative soils of the state. P extracted by M1 and M3 before crop planting was adjusted to P contents in biomass, considering soil buffer capacity. The division of soils into different buffering classes, based on soil clay or remaining P, improved the capacity of estimating soil available P of both methods. However, there was no difference among the correlation coefficients obtained by classifying soils according to the evaluated indexes (remaining P or soil clay) for both M1 and M3 methods. Remaining P is a viable alternative to replace soil clay content to classify soil P extracted with the M1 and M3 methods.

Index terms: clay content, phosphate buffer capacity, phosphate fertilization, phosphorus adsorption, soil test.

# Fósforo remanescente para determinar a disponibilidade de fósforo em solos do Rio Grande do Sul

Resumo – O objetivo deste trabalho foi avaliar o P remanescente comparado ao teor de argila como índice tampão para classificar o P extraído pelos métodos de Mehlich-1 (M1) e Mehlich-3 (M3), em solos do Rio Grande do Sul. O experimento foi realizado em delineamento inteiramente casualisado, com cinco doses de $P_2O_5$ (0, 50, 100, 200 e 400 mg kg$^{-1}$), dois cultivos sucessivos de milho, e três repetições, em 20 solos representativos do Estado. O P extraído pelos métodos M1 e M3, antes dos cultivos, foi ajustado aos conteúdos de P na biomassa, tendo-se considerado a capacidade tampão do solo. A divisão dos solos em classes de tamponamento, de acordo com o teor de argila ou com o P remanescente, melhorou a capacidade preditiva do P disponível para ambos os métodos. Todavia, não houve diferença entre os coeficientes de correlação obtidos pela classificação dos solos de acordo com os índices avaliados (P remanescente ou teor de argila), tanto para o método M1 como para o M3. A análise do P-rem é uma alternativa viável para substituir o teor de argila na classificação do P extraído pelos métodos M1 e M3.

Termos de indexação: teor de argila, fator capacidade de fósforo, adubação fosfatada, adsorção de fósforo, análise de solo.

## Introduction

It is difficult and complex to predict the availability of soil phosphorus for plants. This element binds to the solid phase of the soil with varying degrees of strength. Its availability to plants is inversely related to this soil binding energy (Gatiboni et al., 2007; Fernandez et al., 2008). Phosphorus availability depends on the intensity (I) factor (soil solution), and the quantity (Q) factor (amount of P in the solid phase that supplies I) (Novais et al., 2007; Santos et al., 2008). I and Q are closely correlated with each other. The availability of P is measured by accessing the fraction of Q that desorbs phosphorus to restore I. The most effective method indicates a high correlation between the amounts of P extracted and absorbed and crop yield.

The soil analysis laboratories in the states of Rio Grande do Sul, Santa Catarina, Minas Gerais, Paraná, and Pernambuco use the Mehlich-1 method to estimate the amount of P available to plants (Manual…, 2004). However, this method has some limitations. It overestimates the availability of P in soils fertilized with natural phosphates (Kaminski & Peruzzo, 1997; Oliveira et al., 2015). It is also very sensitive to the P buffering capacity of the soil, which reduces P extraction as it increases (Bahia Filho et al., 1983; Alcântara et al., 2008; Bortolon & Gianello, 2008; Simões Neto et al., 2011; Schlindwein et al., 2013). The Mehlich-3 method has been proposed as a replacement for Mehlich-1 because it extracts more elements than the latter and does not overestimate P availability in soils fertilized with natural phosphates (Bortolon et al., 2009; Oliveira et al., 2015). However, this method is also sensitive to the buffering capacity of the soil (Schlindwein & Gianello, 2008; Bortolon et al., 2011). To compensate for these deficiencies and accurately determine the amount of P extracted, soils are separated by buffering capacity. For soils in Rio Grande do Sul and Santa Catarina, the selection criterion is the clay content, which is inversely proportional to the amount of extractable P (Manual…, 2004).

The clay content is simply a quantitative index of the buffering capacity of the soil. It provides no information about the composition of the fraction. The diversity of geology, climate, topography, soil formation processes and other factors in states of Rio Grande do Sul and Santa Catarina have produced a wide variety of soil types. Soils in the "Campanha Gaúcha" region have twice the amount of clay than those in other areas, whereas those in "Planalto" have a 1:1 clay mineral ratio of iron and aluminum oxyhydroxides. Therefore, these two soil types should have very different buffering capacities. Several studies showed the effect of mineralogy on the adsorption capacity of P (Bahia Filho et al., 1983; Vilar et al., 2010; Gonçalves et al., 2011). However, the current classification system (Manual…, 2004) assumes that soil types within the same clay class all have similar P buffering capacities despite the significant differences in their mineralogies.

The hydrometer method (Tedesco et al., 1995) is routinely used in laboratories to determine clay content but is time consuming, costly, and prone to many analytical errors. In no-tillage systems where organic matter accumulates, clay dispersion is low and, consequently, analytical laboratories often underestimate the clay content in these types of soil (Donagemma et al., 2008; Miyazawa & Barbosa, 2011).

In view of the limitations of analytical methods based on soil texture, other indices of soil buffering capacity have been evaluated. The remaining P (P-rem) method is an adaptation (Alvarez V. et al., 2000) of the technique known as single-value sorption proposed by Bache & Williams (1971). P-rem is being used in certain Brazilian states to classify soils by their buffering capacities (Alvarez V. et al., 1999; Wadt & Silva, 2011). P-rem is faster, simpler, and more accurate than textural determination. P-rem directly evaluates the potential for P immobilization, whereas the clay content does so only indirectly (Alvarez V. et al., 2000). In the near future, soil analyses based on P-rem may indicate the risk of phosphorus leaching from soils into aquatic environments. This analysis could also be used to calculate environmental indices like the degree of P saturation (Moody, 2011) if it has first been calibrated for the particular soil and climate conditions of the region under investigation.

The objective of this work was to evaluate remaining P, compared with soil clay content, as a P buffer index to classify P extracted by the Mehlich-1 (M1) and Mehlich-3 (M3) methods in soils from the state of Rio Grande do Sul, Brazil.

## Materials and Methods

Twenty samples of the main soil classes in the state of Rio Grande do Sul were obtained. Priority was given to those of higher agricultural quality. The samples were collected from the 0–20-cm layer, and preference was given to areas under natural vegetation. After collection, the soils were air-dried, sieved through a 2.0-mm mesh, homogenized, and physicochemically analyzed (Table 1). In addition, farmers in various sites of Rio Grande do Sul sent another 200 samples to the soil analysis laboratory of the Department of Soils of Universidade Federal do Rio Grande do Sul (UFRGS).

The following soil properties were measured: aqueous pH (pH-$H_2O$), soil organic matter (SOM), cation exchange capacity (CEC), titratable acidity ($H+Al^{3+}$), and macro- and micronutrient levels (Tedesco et al., 1995). The clay content of the 20 representative soils was determined by the pipette (Claessen, 1997) and hydrometer (Tedesco et al., 1995) methods for the other 200 soil samples. P-rem was measured by adding 5.0 $cm^3$ soil to a 100-mL conical flask containing 50 mL of a solution composed of 60 mg $L^{-1}$ P and 10 mmol $L^{-1}$ $CaCl_2$. The suspension was stirred for 5 min on a helical motion shaker and left to stand 16 hours (Alvarez V. et al., 2000). The P in the extract was determined with the 7200 Perkin-Elmer inductively coupled plasma-optical emission spectrometer (ICP-OES) (Sikora et al., 2005).

The experiment was conducted using pots placed on an open field at the Department of Soils of UFRGS (51°13'9"W, 30°01'53"S, at an altitude of 10 m). The climate of the region is Cfa according to Köppen's classification (humid subtropical, with hot and humid summers). Two successive corn (*Zea mays* L.) crops were sown and harvested in the same pots between January and March 2013.

Soils whose pH-$H_2O$ was <6.0 were amended with a mixture of CaO and MgO in a 3:1 stoichiometric ratio. The soils were also treated with a micronutrient solution containing 4.0 mg $kg^{-1}$ Cu and Zn, 1 mg $kg^{-1}$ B, and 0.1 mg $kg^{-1}$ Mo. The soils whose S and Mg levels were below the range of "very high" (Manual…, 2004), 45.0 and 42.5 mg $kg^{-1}$ were added, respectively. Soils with K levels <250 mg $kg^{-1}$ were fertilized with KCl. Nitrogen was applied at sowing and during growth, and the total dose was equivalent to 125 mg $kg^{-1}$ N in the form of urea.

The experiment consisted of 20 different soils, five P doses, and three replicates in a completely randomized design. During cultivation I, increasing doses of $P_2O_5$ (0, 50, 100, 200, and 400 mg $kg^{-1}$) were added to the soil in the form of powdered superphosphate (STF). In cultivation II, another 550 mg $kg^{-1}$ $P_2O_5$ were added to the treatment that had already received 50 mg $kg^{-1}$ during cultivation I. This dose was applied to the 15 (of 20) soils with high P-adsorption capacity. For these soils, shoot dry weight was directly proportional to the doses of P applied in cultivation I. The corn crops were sown on January 10 and February 20, 2013.

**Table 1.** Physicochemical characteristics of the studied soils.

| No | Label | Brazilian soil classification(1) | Collection site | pH | SOM(2) (g $dm^{-3}$) | H+Al(3) | CTC(4) | P(4) (mg $dm^{-3}$) | Clay(5) (g $kg^{-1}$) | P-rem(6) (g $L^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | ---(cmol$_c$ $dm^{-3}$)--- | | | | |
| 1 | PBAC | Argissolo Bruno-Acizentado | Soledade | 4.8 | 46 | 14.6 | 20.6 | 8.0 | 478 | 4.9 |
| 2 | PVd | Argissolo Vermelho distrófico | Viamão | 5.2 | 13 | 2.0 | 3.5 | 3.8 | 90 | 47.5 |
| 3 | PVA-1 | Argissolo Vermelho-Amarelo | Cachoeira do Sul | 5.5 | 35 | 3.5 | 23.1 | 13.7 | 256 | 16.4 |
| 4 | PVAd | Argissolo Vermelho-Amarelo distrófico | Tupanciretã | 4.8 | 12 | 4.1 | 5.6 | 11.2 | 162 | 29.8 |
| 5 | PVA-2 | Argissolo Vermelho-Amarelo | São Gabriel | 5.2 | 26 | 5.5 | 11.8 | 9.6 | 248 | 23.9 |
| 6 | CX | Cambissolo Háplico | Carlos Barbosa | 5.2 | 28 | 5.2 | 10.1 | 7.6 | 351 | 14.7 |
| 7 | CHa-1 | Cambissolo Húmico alumínico | São Francisco de Paula | 4.8 | 100 | 27.4 | 28.0 | 4.9 | 190 | 0.5 |
| 8 | CHa-2 | Cambissolo Húmico alumínico | Vacaria | 4.7 | 56 | 14.6 | 18.4 | 5.9 | 573 | 3.0 |
| 9 | MEk | Chernossolo Ebânico carbonático | Aceguá | 5.8 | 41 | 3.7 | 22.0 | 9.0 | 510 | 22.6 |
| 10 | MEo | Chernossolo Ebânico ortico | Caçapava do Sul | 5.5 | 48 | 6.2 | 20.4 | 7.0 | 289 | 18.3 |
| 11 | MXo | Chernossolo Háplico ortico | Taquara | 6.2 | 27 | 1.8 | 16.0 | 33.9 | 130 | 33.8 |
| 12 | LVaf | Latossolo Vermelho aluminoférrico | Erechim | 4.3 | 46 | 23.1 | 25.2 | 5.9 | 641 | 1.9 |
| 13 | LVdf | Latossolo Vermelho distroférrico | Boa Vista das Missões | 4.8 | 31 | 4.9 | 9.8 | 5.1 | 690 | 7.9 |
| 14 | LVd-1 | Latossolo Vermelho distrófico | Passo Fundo | 4.7 | 28 | 10.3 | 13.1 | 4.9 | 354 | 7.7 |
| 15 | LVd-2 | Latossolo Vermelho distrófico | Cruz Alta | 4.8 | 29 | 5.2 | 8.2 | 4.4 | 458 | 7.7 |
| 16 | LVef | Latossolo Vermelho eutroférico | Ibirubá | 5.5 | 33 | 3.9 | 12.5 | 10.6 | 412 | 14.1 |
| 17 | RR | Neossolo Regolítico | Bagé | 5.2 | 44 | 5.5 | 17.3 | 8.2 | 271 | 26.4 |
| 18 | NVdf | Nitossolo Vermelho distroférico | Rodeio Bonito | 5.5 | 28 | 3.5 | 10.5 | 4.3 | 510 | 13.4 |
| 19 | SXe | Planossolo Háplico eutrófico | Cachoeira do Sul | 5.9 | 24 | 3.1 | 12.7 | 10.0 | 109 | 39.3 |
| 20 | VEo | Vertissolo Ebânico ortico | Uruguaiana | 5.9 | 58 | 2.9 | 29.6 | 8.0 | 460 | 19.2 |
| Average | | | | 5.2 | 38 | 7.6 | 15.9 | 8.8 | 359 | 17.6 |
| Medium | | | | 5.2 | 32 | 5.0 | 14.5 | 7.8 | 352 | 15.5 |
| Maximum | | | | 6.2 | 100 | 27.4 | 29.6 | 33.9 | 690 | 47.5 |
| Minimum | | | | 4.3 | 12 | 1.8 | 3.5 | 3.8 | 90 | 0.5 |
| CV, coefficient of variation (%) | | | | 9.0 | 51 | 93 | 46 | 73 | 50 | 73.1 |

(1)Classification according to Santos et al. (2013). (2)SOM, soil organic matter by wet digestion. (3)H+Al per SMP solution. (4)CTC at pH 7.0 and P extracted by the Mehlich-1 method according to Tedesco et al. (1995). (5)Clay by the pipette method (Claessen, 1997). (6)P-rem, Premaining after the application of a 60 mg $L^{-1}$ P solution (Alvarez et al., 2000).

The experimental units consisted of 8-L polyethylene pots. For each treatment, 18 kg dry soil (sufficient for the three replicates) were placed in a cement mixer with the corresponding dose of P. The mixer opening was sealed and the contents homogenized for 3 min. The soil was then removed from the mixer, subdivided into three equal (6 kg) parts, and packed into the pots. The soil was moistened to field capacity (Claessen, 1997), and the pots were distributed randomly in an open field where they would be exposed to outdoor weather conditions.

In cultivation I, eight Pioneer 30F53 hybrid corn seeds were sown per pot 10 days after the treatments were applied. After germination, five seedlings per pot were removed and the remaining three continued to grow for 20 days. When necessary, the pots were irrigated to replenish lost water. Some of the pots were weighed to ensure that soil moisture was maintained close to field capacity. At the end of the growing period, the plants were cut down to 1.0 cm above soil level, dried in a forced-air oven at 65°C, weighed to determine the dry matter of the upper part (DMUP), and ground in a Wiley cutting mill. The P in the plant tissue was later extracted according to Tedesco et al. (1995). The P in the extract was determined by ICP-OES. The absorbed P was quantified by multiplying the tissue P concentration by the DMUP.

Before sowing the corn in each cultivation, soil samples were collected with an earth auger (sampling tube) to evaluate the available P. Three subsamples were collected per pot, blended, and dried in a forced-air oven at 45°C. The dried samples were ground in a porcelain mortar, and the P was extracted using Mehlich-1 (M1) (Tedesco et al., 1995) and Mehlich-3 (M3) solutions (Schlindwein, 2003). The P in the extract was determined by ICP-OES. The quantities of P were determined volumetrically, but the soil densities used to calculate P were recorded in mass units. All measurements were made in duplicate, and the data were presented as averages.

The results were subjected to analysis of variance by at 5% probability. When the correlations were found to be significant, the data were adjusted by the regression analysis. This correction was based on the amount of P absorbed (P-abs) as a function of the soil P content extracted by the M1 and M3 solutions. P-abs was the dependent variable and extracted P was the independent variable. Regressions of P-abs and the P extracted by M1 and M3 were made with and without segregating the soils by buffering criterion (P-rem or clay content). When the clay content of the soil was used as an index, the soils were separated into four classes according to Manual… (2004). When P-rem was used, however, soils were segregated by choosing the bands showing the highest coefficients of determination ($R^2$) between P-abs and the available P according to M1.

Student's t-test for paired averages was used to compare between methods and indices. The methods were also tested by linear regression at a 95% confidence interval. The values of "a" (intersection) and "b" (slope) were compared against the ideal values 0 (zero) and 1 (unity), respectively (Miller & Miller, 2005).

The magnitude of the changes caused by using P-rem as the buffering capacity index was determined by simulating the phosphate fertilization doses recommended for the studied soils. These recommendations were based on a corn crop with an expected yield of 6,000 kg $ha^{-1}$ and the soil amendment and maintenance suggested by Manual… (2004). The available P according to M1 was interpreted using the clay contents as a buffering capacity index according to Manual… (2004) and P-rem.

## Results and Discussion

The analyses of all soils to which different P doses were applied indicated higher levels of P extracted by M3 than by M1 (Figure 1). The angular coefficient (b) of the linear equation fitted between M3(y) and M1(x) was >1. Therefore, M3 extracted, on average, 20% more P than M1. However, there was no significant difference between the two methods ($t = -0.69^{ns}$). However, according to Miller & Miller (2005), when the extractors are compared, it is preferable to check for the value "1" in the confidence interval of the predicted angular coefficient rather than run Student's t-test for paired averages. Upon individual analysis of the soils with $P \leq 21$ mg $kg^{-1}$ – the upper limit of the high band of class IV (Manual…, 2004) –, it was found that the intercept (a) did not differ from 0, and the angular coefficient (b) was not different from 1. These results indicate that there was no significant difference in the P levels between M1 and M3 for this band of values.

When the soils were separated into four clay classes, a significant difference between M1 and M3 was found only for class IV (0–200 g $kg^{-1}$ clay). In this class, M3 extracted higher levels of P than M1 since


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the angular coefficient was 1.25, not a unit. These results corroborate the findings of Bortolon & Gianello (2008) for class IV but not those for the other clay classes. These authors observed that for soils with the clay class IV in Rio Grande do Sul, M3 extracted on average 60% more P than M1. For soils with > 600 g kg$^{-1}$ clay, however, M3 extracted 20% less P than M1.

According to most of the literature, M3 extracts more P than M1 (Schlindwein & Gianello, 2008; Bortolon et al., 2009, 2011). However, some studies detected either no differences between the methods (Oliveira et al., 2015) or higher P extraction with M1 than M3 (Gonçalves & Meurer, 2008). Although it has often been claimed, the alleged superiority of M3 over M1 is not always shown, as was the case in the present study for soils with clay content > 200 g kg$^{-1}$.

For the amounts of P absorbed by corn plants and extracted by M1 and M3 (without soil segregation by buffering class), the coefficients of determination ($R^2$) were 0.49 and 0.47 for M1, and 0.51 and 0.53 for M3 in cultivations I and II, respectively (Figure 2). For selecting extraction methods, these coefficients are low because the adjusted function accounts for only half the data variation on average. The sensitivity of the extractors to the buffering capacity of the soil may account for this inadequacy since the soils were not classified by this factor. However, these methods have predictive limitations because the availability of P in the soil is complex and depends on edaphic and climatic factors, as well as on plant physiology. Therefore, these methods may have contributed to the low $R^2$ values (Santos et al., 2008; Bortolon et al., 2009).

The $R^2$ generally increased for methods and crops when soils were segregated by buffering class (Table 2). In the first cultivation and M1 extraction, $0.58 < R^2 < 0.84$ (= 0.67; ss= 0.11) for clay content classification and $0.50 < R^2 < 0.91$ (= 0.69; s= 0.17) for P-rem classification. In the same cultivation and M3 extraction, however, $0.61 < R^2 < 0.67$ (= 0.65; s= 0.02) for the separation by clay content and $0.57 < R^2 < 0.86$ (= 0.70; s= 0.12) for the separation by P-rem. In cultivation II, the $R^2$ were generally the same as or higher than the values obtained without soil classification. For M1, $0.40 < R^2 < 0.69$ (= 0.53; s= 0.11) in the separation by clay content and $0.36 < R^2 < 0.74$ (= 0.59; s= 0.17) in the separation by P-rem. For M3, $0.40 < R^2 < 0.88$ (= 0.64; s= 0.15) for the clay content classification and $0.47 < R^2 < 0.81$ (= 0.64; s= 0.14) for the P-rem classification. These results clearly indicate that the predictive capacities of M1 and M3 improved after the soil types were separated by clay content or P-rem buffering classes. This observation is in alignment with those of other studies that addressed the sensitivity of M1 and M3 to soil buffering capacity

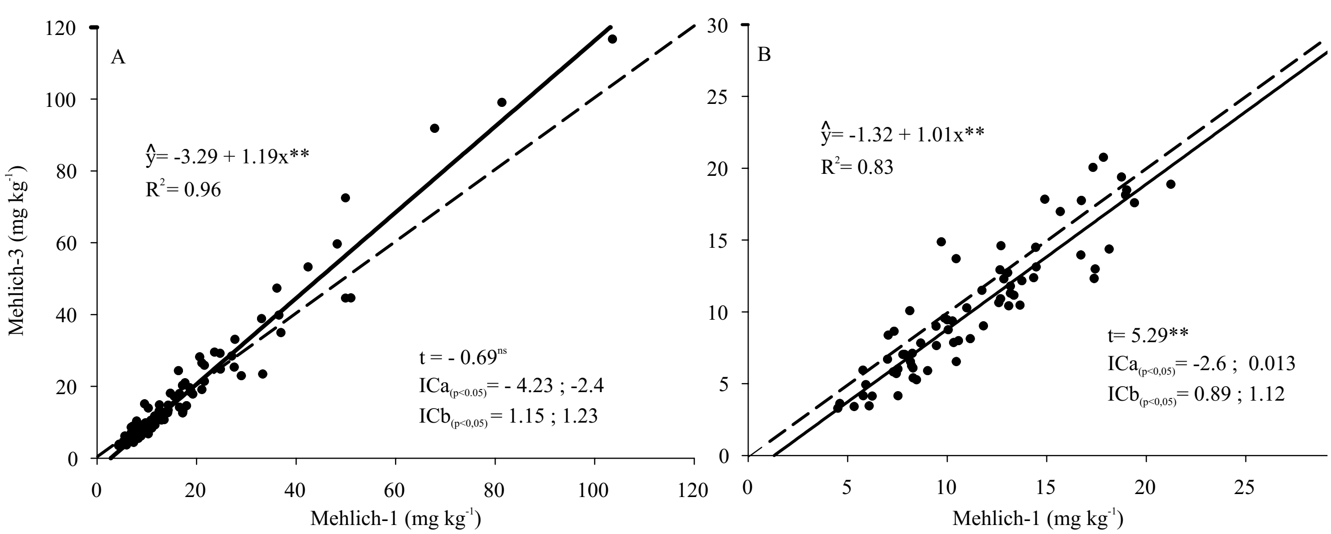


**Figure 1.** P-values extracted by the Mehlich-1 and Mehlich-3 solutions before the first cultivation, for: A, all values; and B, ≤21 mg kg$^{-1}$. The projected dashed line indicates a 1:1 ratio, where the data points would be located if there were 100% compliance between methods. ICa and ICb, confidence intervals at 95% probability of the linear (a) and angular (b) coefficients, respectively. t, Student's t-test for paired means. $^{ns}$Nonsignificant. **Significant at 1% probability.


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(Anghinoni & Bohnen, 1974; Alcântara et al., 2008; Bortolon & Gianello, 2008; Oliveira et al., 2015). Other studies conducted in the state of Rio Grade do Sul (Braida et al., 1996; Schlindwein, 2003) and elsewhere in Brazil (Simões Neto et al., 2011), using the same methods, showed increases in $R^2$ when soils were separated by clay classes. However, there are no reports on the classification of soils in Rio Grande do Sul by P-rem. This information is required in order to improve predictions on the levels of P in agricultural soils and for plant nutrition.

Some studies conducted in the states of Rio Grande do Sul and Santa Catarina over the last few decades showed a wide variability in $R^2$ between the P extracted by M1 and M3 and plant characteristics (Table 3). Experimental conditions differed in terms of the number of soil types, plant species, fertilizer source, application method and timing, and pot volume. The results of these studies revealed the predictive limitations of these methods in various practical situations. In addition, $R^2$ varied significantly, i.e. $R^2 < 0.70$ for M1 and M3 in ~80 and ~60% of the studies, respectively. Since M3 is relatively new, however, there are fewer studies evaluating it than M1. There was no significant difference between the $R^2$ obtained by M1 and M3 for averages paired by equivalent class. This trend was observed in soil classification by clay content

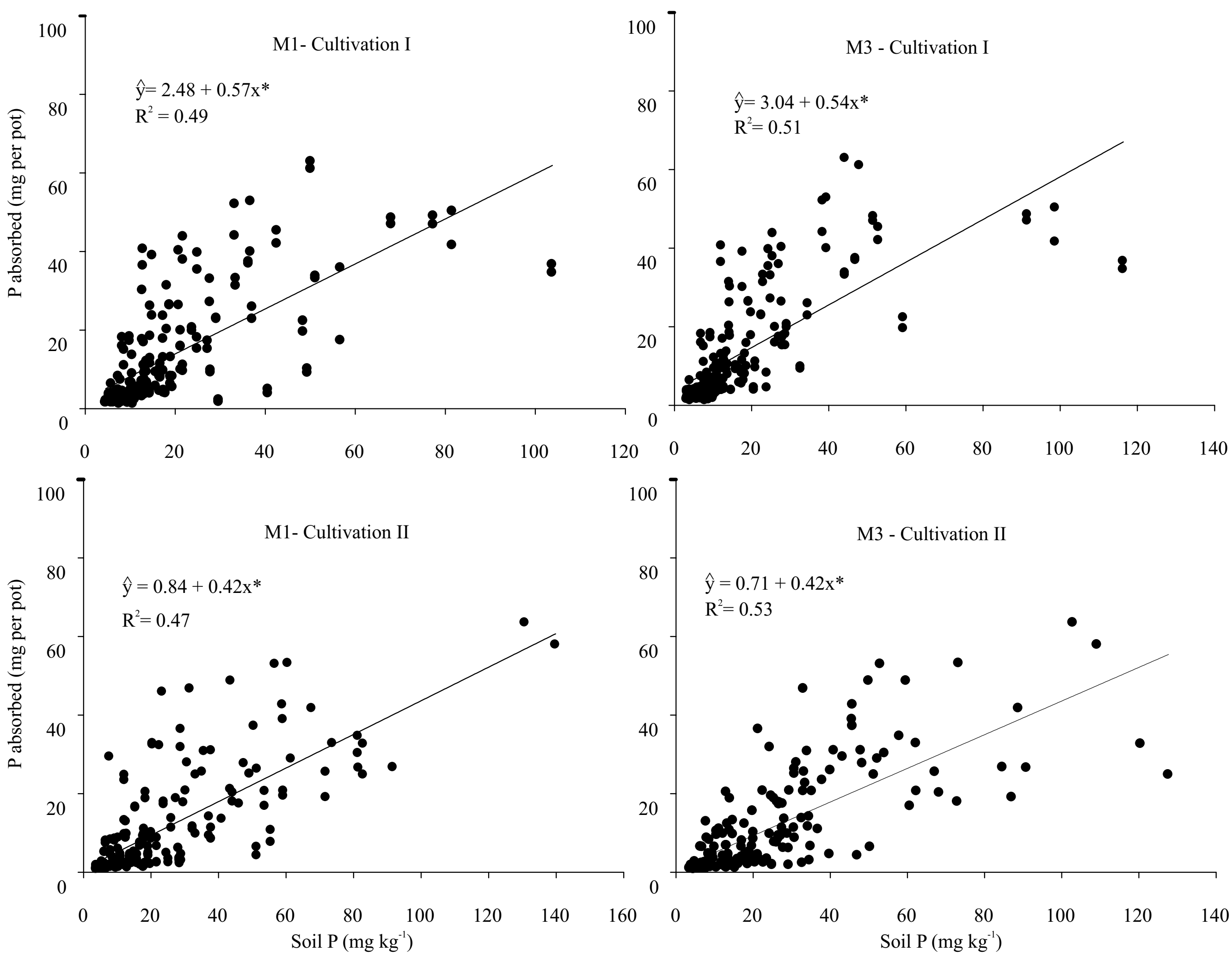


**Figure 2.** Quantities of P absorbed by maize plants and the contents extracted from the crops by the Mehlich-1 (M1) and Mehlich-3 (M3) methods without soil buffering capacity classification.

(t = -0.67ns) and P-rem (t = 1.24ns). For this reason, there is no advantage in replacing M1 by M3 to predict the availability of P for plants. However, the implementation of M3 could increase analytical efficiency in routine laboratory work. As was the case with the present study, Kroth (1998), Gonçalves & Meurer (2008), and Bortolon et al. (2009) reported no significant differences between M1 and M3. It should be noted that, whereas this current study used triple superphosphate as the source of P for plants, Kroth (1998), Gonçalves et al. (2012), and Oliveira et al. (2015) tested natural phosphates. These authors found that M3 was better suited than M1 because

**Table 2.** Coefficients of determination ($R^2$) of P absorbed by corn (*Zea mays*) plants and P extracted by Mehlich-1 and Mehlich-3 with soil separated in buffering capacity classes by clay content and remaining P (P-rem) indices[1].

| Cultivation | Clay content (%) | | | | P-remaining (mg $L^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|
| | >60 | 41–60 | 21–40 | 0–20 | 0–7 | 7.1–15 | 15.1–30 | 30.1–60 |
| | | | | Mehlich-1 | | | | |
| I | 0.84 | 0.64 | 0.57 | 0.64 | 0.90 | 0.64 | 0.58 | 0.64 |
| II | 0.51 | 0.52 | 0.40 | 0.69 | 0.70 | 0.72 | 0.38 | 0.56 |
| | | | | Mehlich-3 | | | | |
| I | 0.67 | 0.61 | 0.67 | 0.64 | 0.84 | 0.69 | 0.67 | 0.56 |
| II | 0.88 | 0.72 | 0.51 | 0.47 | 0.72 | 0.81 | 0.47 | 0.55 |

[1]Classification by clay: class I, ≥60%; class II, 41–60%; class III, 21–40%; and class IV, 0–20% clay. Classification by P-rem: class I, 0–7 mg $L^{-1}$; class II, 7.1–15 mg $L^{-1}$; Class III, 15.1–30 mg $L^{-1}$; Class IV, 30.1–60 mg $L^{-1}$.

**Table 3.** Coefficients of determination ($R^2$) for different P extraction methods using soils in the states of Rio Grande do Sul (RS) and Santa Catarina (SC).

| Number of soils used | State | Variation explained by methods ($R^2 \times 100$) | | | Reference |
|---|---|---|---|---|---|
| | | Mehlich-1 | Mehlich-3 | Resin | |
| 1 | RS | 62 | - | 70 | Fole & Grimm (1973) |
| 40 | RS | 67 | - | - | Anghinoni & Bohnen (1974) |
| 5 | RS | 51 | - | - | Cajuste & Kussow (1974) |
| 4 | RS | 63 | - | 74 | Magalhães (1974) |
| 5 | SC | 64 | - | - | Biasi (1978) |
| 9 | RS | 76 | - | - | Galrão & Volkweiss (1981) |
| 22 | RS | 86 | - | 42 | Rein (1991) |
| 20 | RS | 67 | - | 89 | Miola (1995) |
| 10 | RS | 70 | - | 86 | Braida et al. (1996) |
| 11 | RS | 68 | - | 74 | Silva (1996)[1] |
| 20 | SC | 66 | 62 | 80 | Kroth (1998) |
| 6 | RS | 40 | 75 | 59 | Kroth (1998)[1] |
| 1 | RS | 16 to 99 | - | 13 to 99 | Gatiboni (2003) |
| 18 | RS | 43 to 70 | 34 to 68 | 44 to 81 | Schlindwein (2003)[3] |
| 20 | RS | 57 to 58 | 45 to 57 | 57 | Bortolon (2005) |
| 6 | RS | 83 | 81 | 88 | Gonçalves & Meurer (2008) [1] |
| 16 | RS | 45 | 48 | 70 | Silva et al. (2008)[1] |
| 6 | RS | 88 | 91 | - | Bortolon et al. (2009) |
| 6 | RS | 58 | 61 | - | Gonçalves et al. (2012) [1,2] |
| 1 | SC | 18 | 91 | 85 | Oliveira et al. (2015) [2] |

[1]Rice cultivation in flooded soils. [2]FN, natural phosphate. [3]Field experiment.

the former method solubilizes more effectively the Ca-bound P in this type of fertilizer.

Whether M1 or M3 was used, there was no significant difference between the $R^2$ obtained from soil separation by clay class or P-rem (t = $-1.1^{ns}$). For the $R^2$ between the P absorbed and that extracted by M1 and M3, there was no significant difference between P-rem and clay content in the soil classes. Therefore, P-rem can also separate soils by buffering class to determine P extracted by M1 and M3 (Alvarez V. et al., 2000). The present study has used P-rem soil classification to estimate the P available to plants (Table 4). The limits of the "available" P interpretation bands are the same as those described for the clay content classification system both for M1 (Manual…, 2004) and M3 (Schlindwein & Gianello, 2008).

Soil distribution according to P-rem or the clay index was carried out to assess the practical impact if the classification proposed by the P-rem described in this study was adopted (Figure 3). According to the clay content index, 29, 38, 31, and 2% of the soils are in buffering classes IV, III, II, and I, respectively.

**Table 4.** Interpretation of P content in soil extracted by Mehlich-1 (M1) and Mehlich-3 (M3) methods according to remaining P (P-rem) classes(1).

| Range of interpretation | Soil classes according to P-rem content ($mg\ L^{-1}$)(2) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0–7.0 | | 7.1–15 | | 15.1–30.0 | | 30.1–60 | |
| | M1 | M3 | M1 | M3 | M1 | M3 | M1 | M3 |
| | Available P ($mg\ dm^{-3}$) | | | | | | | |
| Very low | ≤2.0 | ≤2.0 | ≤3.0 | ≤4.0 | ≤4.0 | ≤6.0 | ≤7.0 | ≤10.0 |
| Low | 2.1–4.0 | 2.1–4.0 | 3.1–6.0 | 4.0–7.0 | 4.1–8.0 | 6.1–12.0 | 7.1–14.0 | 10.1–20.0 |
| Medium | 4.1–6.0 | 4.1–6.0 | 6.1–9.0 | 7.1–10.0 | 8.1–12.0 | 12.1–18.0 | 14.1–21 | 20.1–30.0 |
| High | 6.1–12.0 | 6.1–12.0 | 9.1–18.0 | 10.1–20.0 | 12.1–24.0 | 18.1–36.0 | 21.1–42.0 | 30.1–60.0 |
| Very high | >12.0 | >12.0 | >18.0 | >20.0 | >24.0 | >36.0 | >42.0 | >60.0 |

(1)Interpretation proposal using fertility ranges suggested by Manual… (2004) for the Mehlich-1 method and according to the bands proposed by Schlindwein & Gianello (2008) for the Mehlich-3 method. (2)P-rem is the equilibrium solution P concentration after mixing 5 $cm^3$ soil mixed with 50 mL 10 mmol $L^{-1}$ $CaCl_2$ solution containing 60 mg $L^{-1}$ P and stirring 5 min.

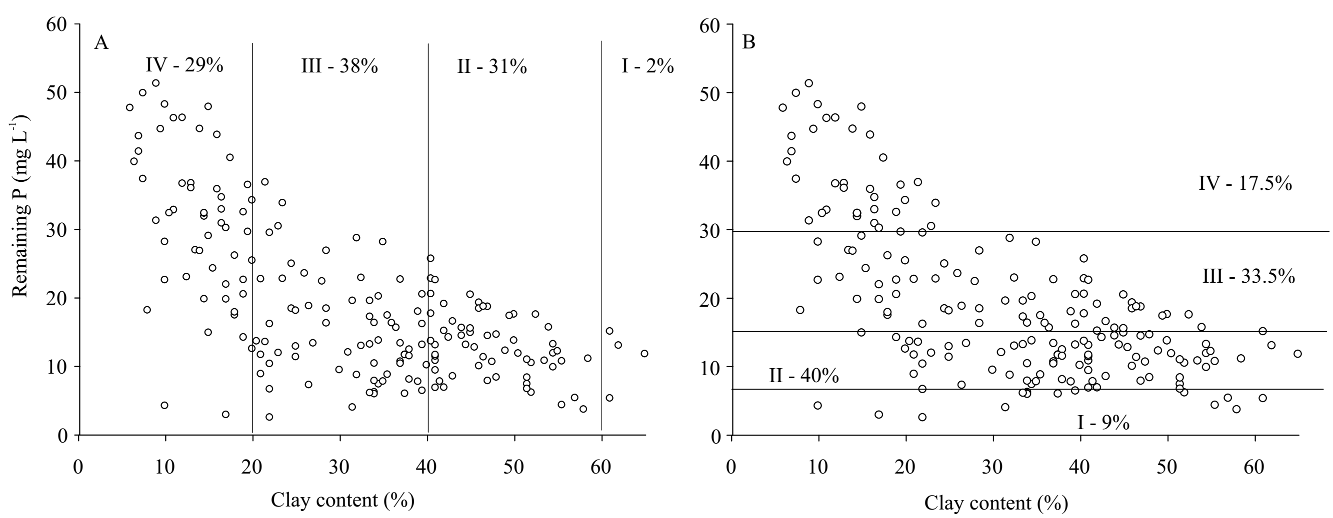


**Figure 3.** Sample distribution by the soil clay content index class (200 samples). Soil classification based on clay content: class I, > 60%; class II, 41–60%; class III, 21–40%; and class IV, <20% (Manual…, 2004); B, soil classification based on remaining P (60 mg $L^{-1}$): class I, 0–7 mg $L^{-1}$; class II, 7.1–15 mg $L^{-1}$; class III, 1–30 mg $L^{-1}$; and class IV, 30.1–60 mg $L^{-1}$.

Using the P-rem index, 17.5, 33.5, 40, and 9% of the soils are in the same respective buffering classes. The P-rem index categorizes more soils in classes I and II and fewer in classes III and IV than the clay content index. Therefore, P-rem caused a higher migration of soils to the more buffered classes and compensated for the limitations of the Mehlich extractor. Relative to the clay content index, P-rem increases the number of soils whose critical P content can be effectively reduced.

P-rem reassigned 9 of the 20 soils studied to buffering classes different from those determined for them using the clay content index (Table 5). Six of these soils (CHa-2, PBAC, LVd, CX, CHa-1, and PVa-2) migrated to higher buffering classes and the other three (LVdf, VEo2, and MEk) were moved to lower buffering classes. Eight soils were only shifted over to the next class when the index was changed. CHa-1, however, migrated from class IV (clay content index) to class I (P-rem index). The recommended superphosphate doses differed between the two indices by ±30 kg ha$^{-1}$ for seven of the nine aforementioned soils. The exception was CHa-1, whose recommended $P_2O_5$

**Table 5.** Simulated classification, interpretation, and recommendation of phosphate fertilization for the studied soils, and hypothetical use of remaining P (P-rem) as a substitute for clay content as a buffering capacity index(1).

| Soil(2) | Collection site | Clay | | | P-rem | | | No. of Classes(7) | P doses(8) (kg ha$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| | | Class(3) | Range(4) | C+M(5) | Class(6) (kg ha$^{-1}$) | Range(4) | C+M(5) (kg ha$^{-1}$) | | |
| PVA1 | Cachoeira do Sul | III | High | 65 | III | High | 65 | 0 | 0 |
| PVA2 | Tupanciretã | IV | Low | 125 | III | Medium | 95 | +1 | -30 |
| PVA3 | São Gabriel | III | Medium | 95 | III | Medium | 95 | 0 | 0 |
| RR | Bagé | III | Medium | 95 | III | Medium | 95 | 0 | 0 |
| MEk | Aceguá | II | Medium | 95 | III | Medium | 95 | -1 | 0 |
| VEo2 | Uruguaiana | II | Medium | 95 | III | Low | 125 | -1 | +30 |
| MEo | Caçapava do Sul | III | Low | 125 | III | Low | 125 | 0 | 0 |
| SXe | Cachoeira do Sul | IV | Low | 125 | IV | Low | 125 | 0 | 0 |
| MXo | Taquara | IV | High | 65 | IV | High | 65 | 0 | 0 |
| CHa1 | São Francisco de Paula | IV | Very low | 185 | I | Medium | 95 | +3 | -90 |
| CX | Carlos Barbosa | III | Low | 125 | II | Medium | 95 | +1 | -30 |
| LVd | Passo Fundo | III | Low | 125 | II | Low | 125 | +1 | 0 |
| LVaf | Erechim | I | Medium | 95 | I | Medium | 95 | 0 | 0 |
| NVdf | Rodeio Bonito | II | Low | 125 | II | Low | 125 | 0 | 0 |
| LVdf | Boa Vista das Missões | I | Medium | 95 | II | Low | 125 | -1 | +30 |
| PBAC | Soledade | II | Medium | 95 | I | High | 65 | +1 | -30 |
| PVd | Viamão | IV | Very low | 185 | IV | Very low | 185 | 0 | 0 |
| LVef | Ibirubá | II | High | 65 | II | High | 65 | 0 | 0 |
| LVd | Cruz Alta | II | Low | 125 | II | Low | 125 | 0 | 0 |
| CHa2 | Vacaria | II | Medium | 95 | I | High | 65 | +1 | -30 |

(1)In the simulation, the same number of buffering classes and critical levels assigned to each class for clay content were used for P-rem according to Manual… (2004). (2)PVA1, Argissolo Vermelho-Amarelo; PVA2, Argissolo Vermelho-Amarelo; PVA3, Argissolo Vermelho-Amarelo; RR, Neossolo Regolítico; MEk, Chernossolo Ebânico carbonático; VEo2, Vertissolo Ebânico ortico; MEo, Chernossolo Ebânico ortico; SXe, Planossolo Háplico eutrófico; MXo, Chernossolo Háplico ortico; CHa1, Cambissolo Húmico alumínico; CX, Cambissolo Háplico; LVd, Latossolo Vermelho distrófico; LVaf, Latossolo Vermelho aluminoférrico; NVdf, Nitossolo Vermelho distroférico; LVdf, Latossolo Vermelho distroférrico; PBAC, Argissolo Bruno-Acizentado; PVd, Argissolo Vermelho distrófico; LVef, Latossolo Vermelho eutroférrico; LVd, Latossolo Vermelho distrófico; and CHa2, Cambissolo Húmico alumínico. (3)Clay classes: class I, >60%; class II, 41–60%; class III, 21–40%; and class IV, 0–20%. (4)Interpretation ranges of P content extracted by the Mehlich-1 method according to Manual... (2004). (5)$P_2O_5$ dose (amendment + maintenance) for an estimated 6,000 kg ha$^{-1}$ corn yield. (6)P-rem classes: class I, 0–7 mg L$^{-1}$; class II, 7.1–15 mg L$^{-1}$; class III, 15.1–30 mg L$^{-1}$; and class IV, 30.1–60 mg L$^{-1}$. (7)Number of classes migrated using the P-rem buffering capacity index, in which (-) migrated to lower buffering classes and (+) migrated to higher buffering classes. (8)Differences between $P_2O_5$ doses required for 6,000 kg ha$^{-1}$ corn yield using clay content and P-rem indices, respectively.

dose was 90 kg $ha^{-1}$ lower with P-rem than with clay content. CHa-1 showed a high maximum P adsorption capacity (> 2,000 kg $ha^{-1}$ $P_2O_5$) and the highest contents of low-crystallinity Fe and Al of all the soils studied despite its low clay content (<200 g $kg^{-1}$). Therefore, a textural index may be inappropriate for CHa-1 since it is insensitive to clay mineralogy (Rogeri et al., 2016). Low-crystallinity iron and aluminum oxyhydroxides are some of the main components of the clay fraction responsible for P adsorption (Vilar et al., 2010; Gonçalves et al., 2011). Using P-rem instead of the clay content index reassigned 45% of the soils into different buffering classes. It also altered the interpretation band of available P and the superphosphate dose recommendations for 35% of the soils. P-rem reduced $P_2O_5$ dosage for 60% of the latter soils and increased it for the remaining 40% relative to the recommendations obtained from the clay content index.

## Conclusions

1. Segregating soils into buffering classes improves the predictive capacity of the Mehlich-1 and Mehlich-3 methods for available P, whether separated by the clay content or remaining phosphorus.
2. Remaining P is a viable alternative to clay content in the interpretation of the P extracted by the Mehlich-1 and Mehlich-3 methods from the soils of the state of Rio Grande do Sul, Brazil.
3. Compared to the clay content index, P-rem assigns more soils in higher buffering capacity classes and reduces the critical P content for these soils.
4. Within the range of values recommended for differentiation in available P interpretation, there is no difference between the Mehlich-1 and Mehlich-3 methods in terms of extracted P.

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