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ARTICLE

Phosphorus saturation index and water-extractable phosphorus in high-legacy phosphorus soils in southern British Columbia, Canada

Aimé J. Messiga, Camellia Lam, and Yunkun Li

Abstract: Understanding of the risk of phosphorus (P) loss to the environment is crucial to monitor soil P and implement policies for P management. We assessed P sorption characteristics and adapted a P saturation index (PSI) for silage corn and blueberry fields in south coastal British Columbia (BC), Canada. We used 284 composite soil samples with contrasting P levels collected from eight silage corn and 23 blueberry fields across south coastal BC. The P sorption maximum ($S_{\max}$) varied between 982 and 2532 mg P·kg^{-1} and was influenced by aluminum concentration and organic matter content. The degree of P saturation was related to water-extractable P (Pw) by a quadratic regression with $R^2 = 0.85$. A critical Pw = 3.7 mg·kg^{-1} was established across the two cropping systems. The silage corn fields with pH > 5.5 had critical PSI value of 10.4%, and blueberry fields with pH < 4.7 had critical PSI value of 18.0%. These results showed that the risk of P loss from soil in the silage corn was high, but it was low for blueberry because the critical PSI for silage corn fields was lower than for blueberry fields, and therefore, saturation would be more easily reached, even though more P is applied to blueberry fields. The combination of a critical PSI and Pw as agri-environmental indicators will help farmers and professionals to identify fields with risk of P loss, to implement a nutrient management plan, and to monitor how this risk changes with time.

Key words: blueberry and silage corn fields, degree of P saturation, maximum P sorption capacity, P sorption isotherms, risk of P leaching.

Résumé : Il est crucial de bien comprendre le risque que le phosphore (P) fuie dans l'environnement si on veut surveiller cet élément dans le sol et en gérer les réserves par l'adoption de politiques connexes. Les auteurs ont analysé les caractéristiques de la sorption du P et adapté un indice de saturation du P (ISP) pour la culture du maïs d'ensilage et du bleuet sur la côte sud de la Colombie-Britannique, au Canada. À cette fin, ils ont recouru à 284 échantillons composites de sol à la concentration de P contrastante, prélevés dans huit champs de maïs d'ensilage et dans 23 bleuetières de la région. La sorption maximale ($S_{\max}$) du P varie de 982 à 2 532 mg par kg et est influencée par la concentration d'aluminium et la teneur en matière organique. Le degré de saturation en P (DSP) est corrélé à la teneur en P extractible à l'eau (Pw) par une régression quadratique ($R^2 = 0{,}85$). Les auteurs ont établi le seuil critique de Pw (3,7 mg par kg) pour les deux productions végétales. Les champs de maïs d'ensilage dont le sol at un pH supérieur à 5,5 ont un seuil critique de 10,4 % pour l'ISP alors que, dans les bleuetières, où le pH du sol était inférieur à 4,7, cette valeur s'établit à 18,0 %. Ces résultats indiquent qu'il existe un risque élevé de lixiviation du P dans les cultures de maïs d'ensilage, mais que le risque est assez faible dans les bleuetières, le seuil critique de l'ISP étant plus bas dans les premières que dans les secondes, de sorte que le point de saturation est plus facile à atteindre, même quand on applique de l'engrais P aux bleuetières. Le seuil critique de l'ISP et celui de Pw sont des indicateurs agro-environnementaux qui aideront les producteurs et les professionnels à identifier les champs susceptibles de perdre du P et à adopter un plan de gestion des oligoéléments, ainsi qu'à surveiller l'évolution de la situation dans le temps. [Traduit par la Rédaction]

Mots-clés : bleuetière, maïs d'ensilage, degré de saturation du P, sorption maximale du P, isothermes de la sorption du P, risque de lixiviation du P.

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Introduction

The agronomic surplus of phosphorus (P) averages 11.5 Tg $P{\cdot}yr^{-1}$ across the globe due to excess mineral fertilizer and manure P applications above crop removals (Sharpley et al. 2013). The amount of surplus P is further exacerbated by trends that have occurred in livestock production. There is a predominance of confined animal feeding operations that import significant quantities of nutrients in purchased feed. These feeding operations have created imbalances between total amount of P imported to the farm and the land available to apply the resulting manure P (van Dijk et al. 2016). High soil P levels resulting from this P surplus may contribute to water quality impairments, which can last for decades if sound strategies to reduce soil P are not implemented (Carpenter 2008). Utilizing legacy soil P can also have significant agronomic (McDowell et al. 2020; Messiga et al. 2020) and economic benefits (Zhang et al. 2020).

The average annual P surplus that accumulates in soils, as animal manure and synthetic fertilizer, is 3030 Mg (50 kg $P{\cdot}ha^{-1}$) in the lower Fraser Valley, British Columbia (BC), Canada (Bittman et al. 2017). The P surplus in BC raises serious concerns about the efficient use of this non-renewable resource and the impact on soil and water sources. The P surplus is reflected in data collected from BC farms, across the Fraser and North Okanagan Valleys, showing that 89% of fields have soil P concentrations in the excess or very high class, between 100 and 350 mg Mehlich-3 P (P_{M3}) (Kowalenko et al. 2007). In 2014, a report ordered by the Shuswap Lake Integrated Planning Process, indicated that 78% of P entering the tributary rivers of the Shuswap Lake in the Okanagan Valley (BC) originates from livestock-based agriculture (Tri-Star Environmental Consulting 2014). In 2016, a report highlighted high risk of P contamination in the Lower Fraser Valley because of higher livestock density and horticultural production (Reid and Schneider 2019). In 2017, nutrient management options and specific recommendations were developed to address drinking water source protection in the Hullcar Valley and elsewhere in BC (Brandes et al. 2017). Consequently, the need to identify agricultural fields with high soil test P and increased risk of P loss to the environment to implement nutrient management plan (NMP) has intensified in the past 5 yr.

A new Code of Practice for Agricultural Environmental Management was published in early 2019 to guide BC farmers and professionals (Environmental Management Act 2019). The code of practice recommends that the Kelowna test method be included when designing a NMP. The Kelowna extraction method is commonly used as an agronomic soil test P in BC, Alberta, and Saskatchewan (Reid et al. 2019) to identify crop P needs for optimal yields but not to assess the risk of P loss to the environment. The degree of P saturation (DPS) is used worldwide to assess P loss risk because it is strongly correlated with P in runoff and leaching water (van der Zee et al. 1987). The DPS indicates the capacity of a soil to desorb or retain additional P from fertilizer or manure, and it is, therefore, related to the P sorption capacity (PSC) (Renneson et al. 2015). The PSC also referred as P sorption maximum (S_{max}) is influenced by pH, soil texture, organic matter, as well as exchangeable and amorphous aluminum, iron, and calcium contents (Renneson et al. 2015). The PSC is related to aluminum (Al) and iron (Fe) in the acid ammonium oxalate extract and the S_{max} is derived from the Langmiur equation. A DPS of 25% is considered the critical limit above which the risk of P loss increases in acid soils (van der Zee et al. 1987). In North America, including Canada, the oxalate soil extraction method used to assess DPS is not a routine analysis (Dayton et al. 2014). Instead, the P saturation index (PSI) derived from Mehlich-3 P (P_{M3}) and aluminum (Al_{M3}) and (or) iron (Fe_{M3}) is used as a proxy of DPS to assess the risk for P leaching from agricultural soils (Sims et al. 2002; Pellerin et al. 2006; Wang et al. 2012; Benjannet et al. 2018). Advantages of the Mehlich-3 extraction method include the capability to make fertilizer recommendations for P as well as other macro- and micronutrients such as calcium, magnesium, and zinc to achieve optimum yields (Penn et al. 2018). The widespread use and versatility of the Mehlich-3 method in North America and its multielemental characteristic has led to its inclusion into the soil analytical packages of most private laboratories in BC. However, fertilizer guides require the conversion of P_{M3} concentrations into corresponding Kelowna soil test P concentrations when developing NMPs (BC Ministry of Agriculture 2018*a*; Environmental Management Act 2019).

To our knowledge, there is limited information on how PSI is related to DPS or water-extractable P (Pw), two main indicators of the risk of P to the environment, across agricultural soils and cropping systems in south coastal BC. The PSI is influenced by soil pH (Benjannet et al. 2018) and soil texture (Pellerin et al. 2006). Penn et al. (2018) showed that the P extracted by the Mehlich-3 method decreases with increasing soil pH because of changing P forms, partial neutralization of extractant pH, and consumption of extractant fluoride. It was also shown that Mehlich-3 solution extracts more P from coarse soils compared with fine-textured soils (Giroux and Tran 1985). These contrasting effects of soil pH and texture have resulted in different critical PSI values where soil pH and texture vary across the region (Pellerin et al. 2006; Benjannet et al. 2018) and even for different cropping systems (Guérin et al. 2007). The conversion of P_{M3} concentrations to Kelowna P concentrations depends on several factors, and therefore, a simple conversion would not account for the variability associated with Mehlich-3 extraction due to the influence of soil pH or soil texture. It is, therefore, crucial to understand how PSI can simulate or predict Pw concentrations to assess and monitor the risk of P loss.

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Silage corn and blueberries are two major cropping systems in south coastal BC. Silage corn is usually cropped in rotation with grass to provide feed for dairy cows. Annual applications of high amounts of starter fertilizer P and solid and liquid fractions of manure have contributed to the buildup of soil P in silage corn–grass rotation systems (Bittman et al. 2017; Zhang et al. 2018). In addition, reports have also shown that applications of fertilizer P in excess of crop removals have contributed to high-legacy soil P in the majority of blueberry fields in the Fraser valley of BC (Kowalenko et al. 2007; van Bochove et al. 2012; Reid and Schneider 2019). The mixing of elemental sulfur with soil to lower the soil pH in the range 4.2 and 5.5 prior to establishing new blueberry fields is a common practice in south coastal BC. The preferential application of ammonium-based nitrogen (N) fertilizer in blueberry fields because blueberry plants preferentially uptake ammonium over nitrate, further contributes to decreasing soil pH (Messiga et al. 2018). These two major cropping systems with differences in soil pH due to farmers' management including liming of silage corn fields and application of ammonium sulfate fertilizer as source of N to blueberry fields offer a unique opportunity to understand how PSI is affected by soil pH. A better understanding of P dynamics and sorption characteristics and the development or adaption of environmental indicators to develop NMPs specifically tailored for these major cropping systems is needed. The objectives of this study were to (*i*) assess P sorption characteristics to estimate P sorption maximum ($S_{\max}$) relative to other soil properties, (*ii*) adapt a PSI for soils of silage corn and blueberry production systems, and (*iii*) assess the ability of PSI to simulate Pw concentrations across the two cropping systems.

Materials and Methods

Study area and soil sampling

Eight silage corn and 23 blueberry fields located in south coastal BC were considered for this study. The soils in the area belong to the order Brunisolic, Gleysolic, Luvisolic, Podzolic, and Regosolic (Soil Classification Working Group 1998). The minimum and maximum general soil properties across all sites were soil pH: 4.9–6.0, total carbon (C): 0.94%–11.35%, total N: 0.07%–0.82%, and Mehlich-3-extractable P: 3.42–195.32 $mg \cdot kg^{-1}$ (Messiga et al. 2020). Phosphorus fertilization in the silage corn fields included applications of 35 kg $P \cdot ha^{-1}$ as starter and manure P (Messiga et al. 2020). Phosphorus fertilization recommendations in BC blueberry production guides are based on leaf analysis and are well beyond crop removal (BC berries production guide 2018*b*). For example, P fertilizer recommendations for a mature blueberry planting range from 20 to 30 kg $P \cdot ha^{-1}$ for a plant that only exports a maximum of 6 kg $P \cdot ha^{-1} \cdot yr^{-1}$ including fresh fruit and pruning (BC Berry Production Guide 2018*b*).

Soil samples (0–15 cm) were collected in silage corn fields in mid-September after harvest in 2018 and 2019 and in the blueberry fields between June and July 2019. In the silage corn fields, 10 soil cores were randomly collected per plot (10 m × 5 m). In the blueberries, each field (approximately 2.0 ha) was visually divided into four blocks, the layer of sawdust on top of the soil was discarded, and 10 soil cores were randomly collected per block. All soil cores were composited on-site, then air-dried, and passed through a 2 mm sieve before analysis. In total, 284 composite soil samples were collected (8 silage corn fields × 24 plots and 23 blueberry fields × 4 blocks).

The average daily temperature ranges from 3.2 °C in December to 18.8 °C in August [30 yr (1981–2010) average]. The local climate is moderate oceanic, characterized by warm, rainy winters and relatively cool, dry summers with mean annual rainfall of 1689 mm [30 yr (1981–2010) average], 261.9 mm of which falls between May and July (Environment and Climate Change Canada 2020).

Phosphorus sorption experiments

The composite soil samples taken from the corn fields were used for P sorption experiments (Messiga et al. 2011). Blueberry sites were not considered for the sorption experiment given the high number of sites and the workload associated. In brief, solutions with a range of P concentrations were formulated in a matrix of distilled water and 100 μL of toluene (to inhibit microbial activity) for batch equilibration with the soil. Initial equilibrating solution P concentrations were 0, 5, 10, 20, 30, 40, 50, 100, 200, and 300 mg $P \cdot L^{-1}$ as KH_2PO_4. Sorption batches were replicated three times and consisted of 2.0 g air-dried soil mixed in 50 mL centrifuge tubes with 30 mL of the equilibrating solution. The tubes were gently shaken for a 24 h contact time end-over-end at room temperature, centrifuged at 3500 $r \cdot min^{-1}$ for 10 min and then filtered through Whatman Grade 42 filter paper. An aliquot of the supernatant solution was used to determine P in solution. Phosphorus in the extracts was measured by the molybdate blue colorimetric method which involves a redox reaction in which phosphate ions react to form phosphomolybdate before reading at a wavelength of 880 nm (Murphy and Riley 1962).

Soil analyses

Soil pH was measured in distilled water with a 1:2 soil: solution ratio (Hendershot et al. 1993). Total C and N were determined by dry combustion with a LECO CNS-1000 (LECO Corp., St. Joseph, MI, USA). The Pw was determined by shaking 2.0 g of air-dried soil mixed in 50 mL centrifuge tubes with 20 mL distilled water for 1 h, centrifuging the mixture at 3500 $r \cdot min^{-1}$ for 10 min, and filtering through Whatman Grade 42 filter paper (Self-Davis et al. 2000). Phosphorus in the extracts was measured by the molybdate blue colorimetric method (Murphy and Riley 1962). Acid ammonium oxalate-extractable P (P_{Ox}), aluminum (Al_{Ox}), and iron (Fe_{Ox}) were

Table 1. General properties of soils[a] (0–15 cm) collected during a provincial soil survey conducted in south coastal British Columbia (Canada) in 2005.

	Field no.[b]	Clay[c] (%)	Silt (%)	Sand (%)	pH	Total carbon (%)	Total nitrogen (%)	Total phosphorus ($mg \cdot kg^{-1}$)	Al_{M3} ($mg \cdot kg^{-1}$)[d]
Corn/grass									
Brunisolic[e]	31	17	60	24	5.54	2.24	0.20	1366	1253
Gleysolic	82	22	56	21	5.61	4.06	0.32	1762	1132
Luvisolic	2	19	60	20	5.90	3.73	0.33	2259	996
Podzolic	17	10	66	23	5.49	4.73	0.35	2398	1746
Regosolic	1	7	31	62	5.41	1.08	0.09	973	542
Blueberry									
Brunisolic	2	16	65	19	5.09	2.12	0.16	1632	1308
Gleysolic	6	22	43	35	5.10	3.63	0.29	1437	967
Podzolic	12	7	50	44	5.69	2.91	0.21	3228	1698

[a]Soils were collected during a provincial survey conducted in 2005.
[b]Number of fields sampled.
[c]Soil texture (clay, silt, and sand) was determined using the hydrometer method (Day 1965).
[d]Aluminum was extracted using the Mehlich-3 method and analyzed by inductively coupled plasma.
[e]Canadian System of Soil Classification (Soil Classification Working Group 1998).

determined according to Ross and Wang (1993). Mehlich-3-extractable P (P_{M3}), aluminum (Al_{M3}), and iron (Fe_{M3}) were determined by shaking 2.5 g of air-dried soil with a 25 mL of Mehlich-3 solution (pH 2.3) for 5 min (Mehlich 1984). The concentrations of P_{Ox}, Al_{Ox}, Fe_{Ox}, P_{M3}, Al_{M3}, and Fe_{M3} were assessed with an inductively coupled plasma optical emission spectrometer (ICAP 7000 series, Thermo Scientific).

The DPS was calculated as the molar ratio of acid ammonium oxalate extracts as follows (van der Zee et al. 1987):

$$(1) \qquad \mathrm{DPS} = 100 \times \frac{P_{Ox}}{\alpha_m\ (Al_{Ox} + Fe_{Ox})}$$

where P_{Ox}, Al_{Ox}, and Fe_{Ox} are quantified in acid ammonium oxalate extracts ($mmol \cdot kg^{-1}$). The sum of Al_{Ox} and Fe_{Ox} is termed P sorption capacity (PSC, $mmol \cdot kg^{-1}$). The term α_m is the maximum sorption coefficient (van der Zee et al. 1987; Breeuwsma and Silva 1992). We used an average α_m value of 0.5 to calculate DPS (Benjannet et al. 2018).

The PSI was related to Mehlich-3 extracts as follows (Khiari et al. 2000):

$$(2) \qquad \mathrm{PSI} = 100 \times \frac{P_{M3}}{Al_{M3}}$$

where P_{M3} and Al_{M3} are quantified in Mehlich-3 extracts ($mmol \cdot kg^{-1}$).

Statistical analyses

Sorption data for each silage corn site were fitted using Langmuir and Freundlich isotherms. Sorption isotherms were parameterized using PROC NLIN of SAS version 9 (SAS Institute Inc. 2010). The Langmuir isotherms resulted in the best goodness of fit for all sites. The Langmuir isotherm is described as follows:

$$(3) \qquad S = S_{max} \times \frac{k_a \times C}{1 + k_a \times C}$$

where S ($mg\ P \cdot kg^{-1}$) is the sorbed P onto the soil after 24 h contact, S_{max} ($mg\ P \cdot kg^{-1}$) is the P sorption maximum at the highest P concentration, k_a ($L\ mg \cdot P^{-1}$) is the binding energy of P, and C ($mg\ P \cdot L^{-1}$) is the equilibrium P concentration in solution (Messiga et al. 2011). The goodness of fit of the sorption isotherms to experimental data was assessed by the R^2 and standard error of the mean.

Pearson's correlation analysis was performed to assess the linear relationships between S_{max} and selected soil properties using PROC CORR of SAS (SAS Institute Inc. 2014). To determine environmental risk limits, we investigated the relations among DPS, PSI, and Pw. We used the environmental risk limit for DPS = 25% suggested in the Netherlands (van der Zee et al. 1987) to derive the corresponding critical limits for Pw and then PSI. Finally, we plotted PSI vs. Pw values to verify the consistency of the critical risk limits obtained by using DPS. This approach has been used in several studies in North America including Canada (Khiari et al. 2000; Sims et al. 2002; Benjannet et al. 2018). Graphical and numerical approaches using R^2 and standard error of the means were the basis to assess the regressions.

We further used these regressions [$y = f(x)$, where x = PSI and y = Pw] to simulate the trends of Pw concentrations for a wide range of soils found in the southern coast of BC. To achieve this goal, we considered a different dataset (pH, P_{M3}, Al_{M3}, and Pw) retrieved from a soil survey conducted in 2005 across the southern coast of BC (Table 1; Kowalenko et al. 2007). The 2005 soil dataset

Table 2. Phosphorus (P) sorption characteristics derived from the Langmuir equations of soils collected in eight corn sites (0–15 cm) across south coastal British Columbia (Canada) in 2018 and 2019.

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8
S_{max} (mg P·kg^{-1})[a]	2533	2108	2394	2397	1565	1441	948	839
K_a (L mg·P^{-1})[b]	0.008	0.011	0.008	0.015	0.041	0.018	0.004	0.007
P value[c]	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
R^2	0.99	0.96	0.99	0.99	0.93	0.90	0.96	0.94
RMSD	20.40	35.13	19.77	15.15	47.88	45.84	12.89	15.84

Note: RMSD, root means squared deviation.
[a]P sorption maximum.
[b]Binding energy of P.
[c]Significance probability.

included five soil groups (Brunisolic, Gleysolic, Luvisolic, Podzolic, and Regosolic) for corn in rotation with grass and three soil groups (Brunisolic, Gleysolic, and Podzolic) for blueberry production systems. In total, 153 fields were considered from the dataset, including 133 for corn in rotation with grass and 20 for blueberry production systems. The P_{M3} and Al_{M3} from the 2005 soil survey data were determined by the Mehlich-3 method and were used to calculate corresponding observed PSI values (Mehlich 1984). The Pw concentrations from the survey data were determined according to Self-Davis et al. (2000) and were considered as observed Pw concentrations. The analysis of the observed Pw concentrations was performed using an inductively coupled plasma optical emission spectrometer (ICAP 7000 series, Thermo Scientific) instead of colorimetric method. Considering that P concentrations analyzed by inductively coupled plasma (ICP) are generally higher than colorimetric values by 15%–20% (Adesanwo et al. 2013), we considered a scenario with 0.8 × measured Pw concentration. This difference is generally ascribed to the presence of organic P, which is included in ICP determination but not in colorimetric (Adesanwo et al. 2013). Our assumption was that the regressions (PSI vs. Pw) obtained in the present study would fit the observed PSI values and Pw concentrations collected in 2005. In other words, the regressions will simulate observed Pw concentrations using observed PSI values obtained in 2005. We evaluated the robustness of the regressions by plotting observed Pw ($y_{observed}$) concentrations of the 2005 dataset against simulated Pw concentrations ($y_{simulated}$). The R^2, the slope and intercept of the linear regressions, and the root means squared deviation (RMSD) were used to assess the match between $y_{observed}$ and $y_{simulated}$ values (Piñeiro et al. 2008). The RMSD was calculated as follows:

$$\text{(4)} \qquad \text{RMSD} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(y\,\text{simulated}_i - y\,\text{measured}_i)^2}$$

A RMSD value of zero corresponds to a perfect match between simulated and observed Pw concentrations. The closer the RMSD value is to zero, the more accurate the model is.

Results

Phosphorus sorption characteristics of the soils

The experimental data of the sorption study for all eight corn sites were best fitted by the Langmuir equation, with R^2 values ranging between 0.90 and 0.99 (Fig. 1; Table 2). The S_{max} values varied from 476 mg P·kg^{-1} under site 7 to 1914 mg P·kg^{-1} under site 4 (Table 2). The binding energy of P onto sorption sites (k_a value) also varied among sites, from 0.008 L mg·P^{-1} for site 1 to 0.041 L mg·P^{-1} for site 5 (Table 2). Pearson's correlation analyses showed that S_{max} values were significantly related to total C (0.62; $P = 0.001$), PSC (0.42; $P = 0.015$), DPS (−0.43; $P = 0.015$), and Al_{M3} (0.59; $P = 0.001$) (Table 3) for corn/grass sites.

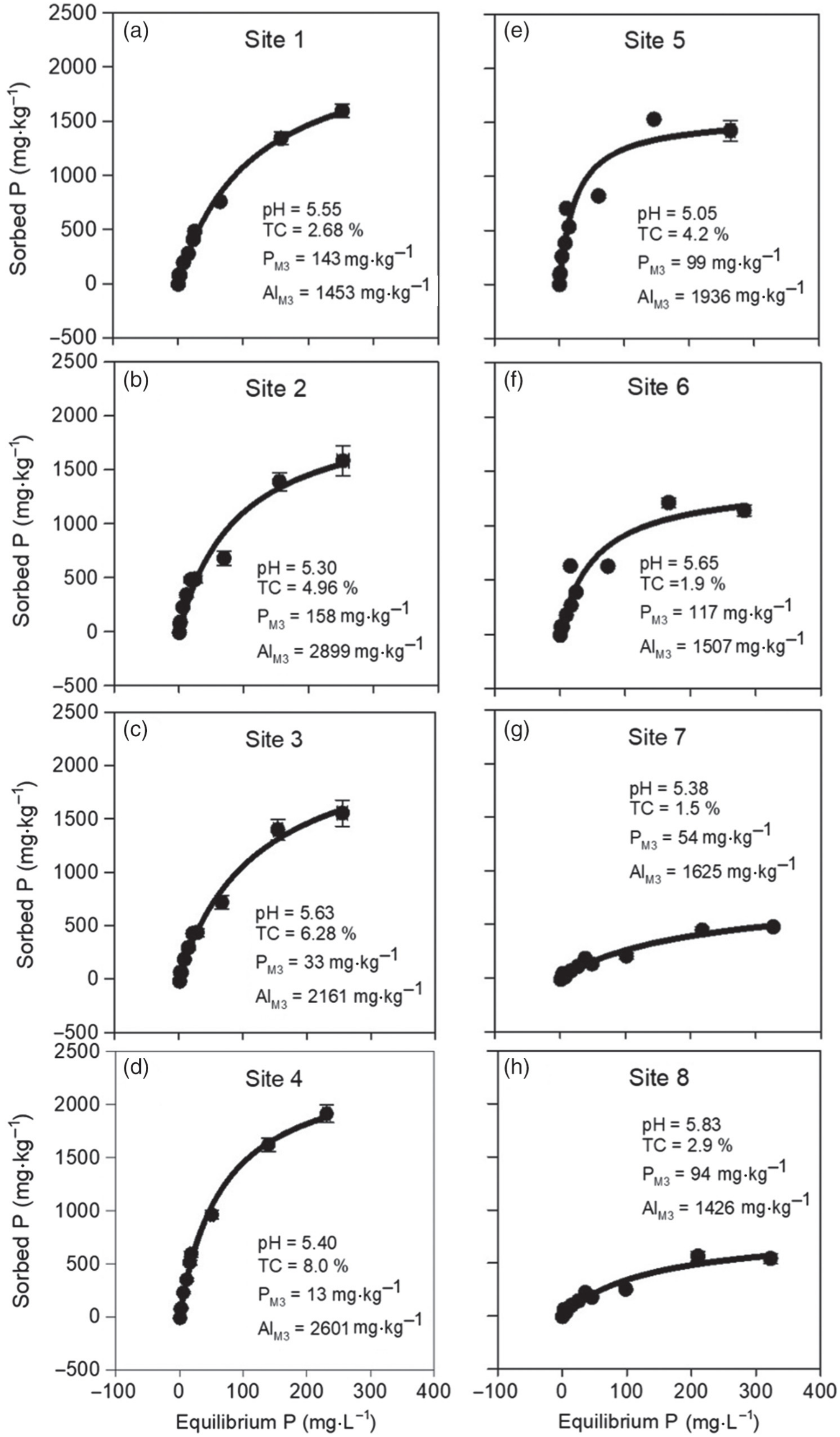
Relationship between DPS and Pw

The DPS varied widely, ranging between 8.2% and 41.5% among the eight corn sites (Fig. 2*a*) and between 4.2% and 26.8% among the 23 blueberry production systems (Fig. 2*b*). The Pw varied between 0.0 and 12.8 mg·L^{-1} (Fig. 2*a*) under the corn production systems and between 0.0 and 6.2 mg·L^{-1} (Fig. 2*b*) among the blueberry sites. The relationship between DPS and Pw was described by quadratic regressions with $R^2 = 0.89$ for the corn (Fig. 2*a*) and $R^2 = 0.86$ for the blueberry sites (Fig. 2*b*). We pooled the two cropping systems, and the relationship between DPS and Pw was also described by a quadratic function with R^2 of 0.85 (Fig. 2*c*). The Pearson's correlations (0.92 across corn and blueberry sites) derived from the R^2 show a strong correlation between DPS and Pw. By using this single quadratic regression and considering a critical DPS of 25% (van der Zee et al. 1987), above which the risk of P loss by runoff water is high, we calculated an average critical Pw concentration of 3.7 mg·L^{-1} (Fig. 2*c*).

Critical PSI estimation

The PSI varied between 2.2% and 28.6% among corn sites and between 0.62% and 26.2% among blueberry sites (Fig. 3). The PSI were related to DPS through a quadratic

Fig. 1. Phosphorus (P) sorption curves for soils collected between 2018 and 2019 in eight silage corn sites across south coastal British Columbia (TC = total carbon; P_{M3} = Mehlich-3-extractable phosphorus; Al_{M3} = Mehlich-3-extractable aluminum).



regression with $R^2 = 0.83$ for the corn sites and a power regression with $R^2 = 0.84$ for the blueberry sites, indicating strong correlations (Fig. 3). To refine our estimates of critical PSI, we related PSI and Pw across the two cropping systems. The relationship between PSI and Pw was described by a linear regression with $R^2 = 0.95$ for corn sites and a quadratic regression with $R^2 = 0.90$ for blueberry sites, indicating strong correlations (Fig. 4).

Table 3. Pearson's correlation coefficients of S_{max} and properties of soils collected in eight corn sites (0–15 cm) across south coastal British Columbia (Canada) in 2018 and 2019.

	S_{max}[a]	pH	TC	P_{Ox}	PSC	DPS	P_{M3}	Al_{M3}	PSI
S_{max}	1.000[b]	−0.25	**0.62**	−0.02	**0.42**	**−0.426**	−0.022	**0.59**	−0.20
	0.001[c]	*0.175*	***0.001***	*0.907*	***0.015***	***0.015***	*0.905*	***0.001***	*0.265*
pH	—	1.00	**−0.44**	−0.17	−0.11	0.07	−0.09	−0.25	0.11
	—	*0.001*	***0.014***	*0.371*	*0.572*	*0.706*	*0.626*	*0.173*	*0.542*
TC	—	—	1.00	−0.23	**0.37**	**−0.63**	**−0.39**	**0.55**	**−0.55**
	—	—	*0.001*	*0.202*	***0.037***	***<0.001***	***0.028***	***0.001***	***0.001***
P_{Ox}	—	—	—	1.00	0.28	**0.61**	**0.73**	−0.14	**0.57**
	—	—	—	*0.001*	*0.121*	***<0.001***	***<0.001***	*0.446*	***<0.001***
PSC	—	—	—	—	1.00	**−0.52**	−0.11	**0.54**	**−0.38**
	—	—	—	—	*0.001*	***0.002***	*0.544*	***0.001***	***0.032***
DPS	—	—	—	—	—	1.00	**0.74**	**−0.65**	**0.88**
	—	—	—	—	—	*0.001*	***<0.001***	*<0.001*	*<0.001*
P_{M3}	—	—	—	—	—	—	1.00	−0.14	**0.84**
	—	—	—	—	—	—	*0.001*	*0.434*	***<0.001***
Al_{M3}	—	—	—	—	—	—	—	1.00	**−0.61**
	—	—	—	—	—	—	—	*0.001*	***<0.001***
PSI	—	—	—	—	—	—	—	—	1.00
	—	—	—	—	—	—	—	—	*0.001*

Note: The pair(s) of variables with positive correlation coefficients and *P* values below 0.050 tend to increase together (**Bold**). For the pairs with negative correlation coefficients and *P* values below 0.050, one variable tends to decrease while the other increases. For pairs with *P* values greater than 0.050, there is no significant relationship between the two variables. TC, total carbon; P_{Ox}, acid ammonium oxalate-extractable phosphorus; PSC, phosphorus saturation capacity (Al + Fe)Ox; DPS, degree of P saturation; P_{M3}, Mehlich-3-extractable phosphorus; Al_{M3}, Mehlich-3-extractable aluminum; PSI, phosphorus saturation index.

[a]P sorption maximum.

[b]Correlation values are in roman.

[c]*P* values are in italic; significance probability at 0.05.

An approximation of the linear regression line shows that, for a critical Pw concentration of 3.7 mg·kg^{-1}, the critical PSI value is 10.4% for the corn sites and 18% for the blueberry sites (Fig. 4). Similarly, if we consider a Pw concentration of 2.0 mg·kg^{-1}, which is considered the lower limit of the risk class, the corresponding PSI is 7.1% for the silage corn sites and 14.4% for the blueberry sites (Fig. 4). Furthermore, a Pw concentration of 5.9 mg·kg^{-1}, which is considered the upper limit of the risk class, corresponds to a PSI of 14.4% for the corn sites and 22.0% for the blueberry sites (Fig. 4).

Comparison between observed and simulated Pw values

The PSI in the soil survey dataset varied between 0.65% and 39.6% for the corn sites and between 2.48% and 41.70% for the blueberry sites. The Pw concentrations varied between 1.86 and 29.00 mg·L^{-1} for the corn sites and between 3.41 and 36.9 mg·L^{-1} for the blueberry sites. The PSI were related to Pw concentrations by a linear regression with $R^2 = 0.72$ for the corn sites (Fig. 5*a*) and a quadratic regression with $R^2 = 0.93$ for the blueberry sites, indicating strong correlations (Fig. 5*b*).

Simulated Pw concentrations paralleled observed concentrations, but the latter were higher than the former for the corn (Fig. 5*a*) and blueberry sites (Fig. 5*b*). The RMSD values for the different set of comparisons (simulated vs. observed Pw) were 5.9 for the corn sites (Fig. 6*a*) and 7.4 for the blueberry sites (Fig. 6*b*). For the scenario with 0.8 × measured Pw concentration, the RMSD value for the comparisons (simulated vs. 0.8 × observed Pw) was 3.7 for the corn and blueberry sites (Figs. 6*a*, 6*b*). In addition, the slopes of the regression lines around a 1:1 line were improved with the new simulations (0.8 × observed Pw values), with 0.71 under the corn sites (Fig. 6*a*) and 1.21 under the blueberry sites (Fig. 6*b*) compared with 0.60 and 0.61, respectively, with the original data (measured Pw). This second set of comparisons (Figs. 6*a*, 6*b*) highlights the differences between colorimetric and ICP in the determination of P in soil extracts and, therefore, suggest the importance for standardized methods.

Discussion

Phosphorus sorption characteristics

Much research on P sorption characteristics of agricultural soils emphasizes the dominant role of Al, Fe, Ca, and organic matter (OM) content and other soil properties, all of which can increase the capacity of soils to fix newly applied P and thus reduce the efficiency of P fertilizers. The present results indicate that, among the

Fig. 2. Relationships between degree of phosphorus (P) saturation and water-extractable P for (*a*) silage corn sites (median soil pH = 5.5), (*b*) blueberry sites (median soil pH = 4.7), and (*c*) all sites in south coastal British Columbia.

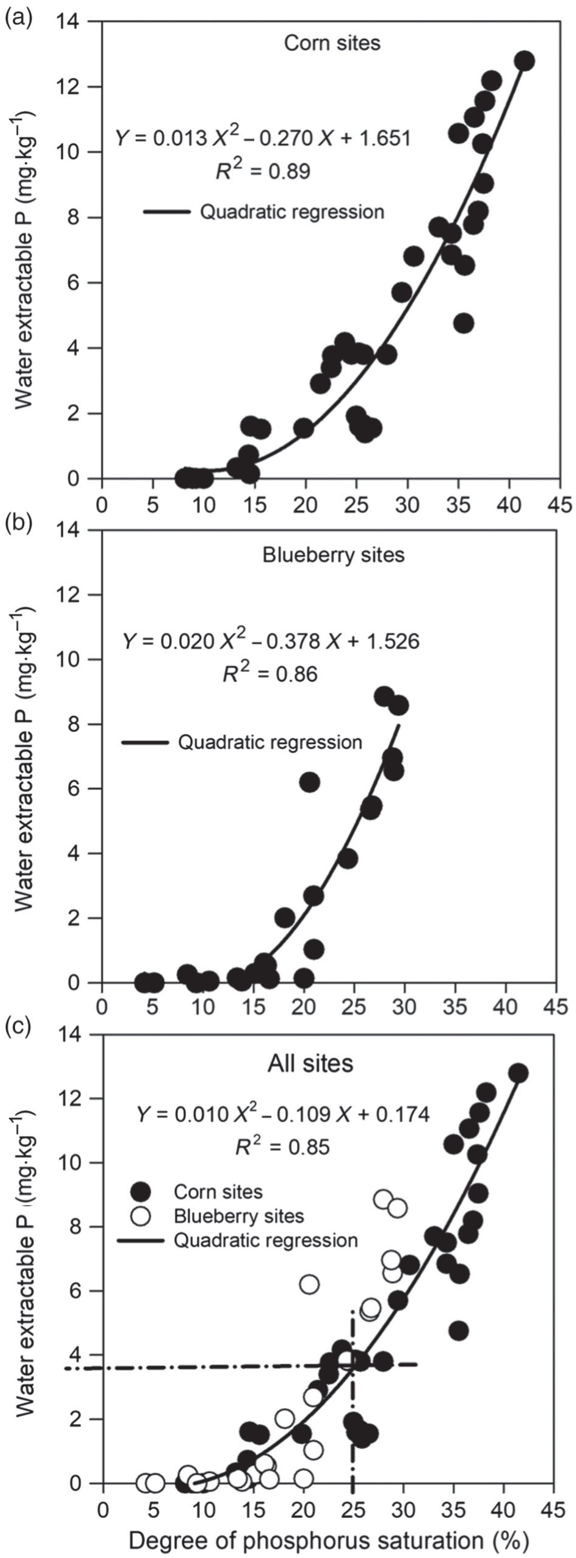


Fig. 3. Relationships between degree of phosphorus (P) saturation and P saturation index for silage corn (median soil pH = 5.5) and blueberry sites (median soil pH = 5.5) in south coastal British Columbia.

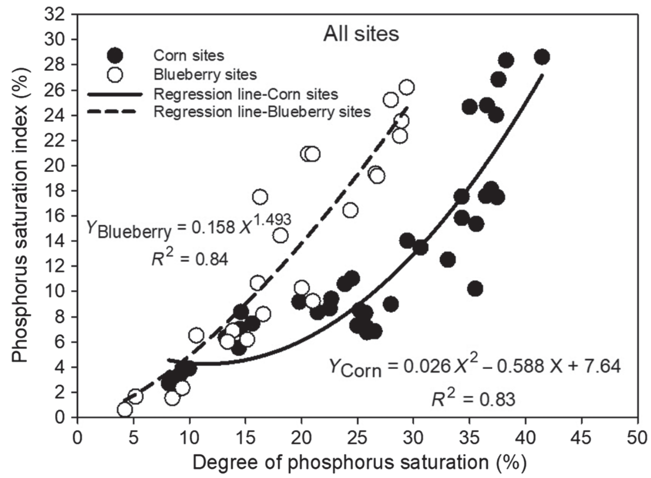
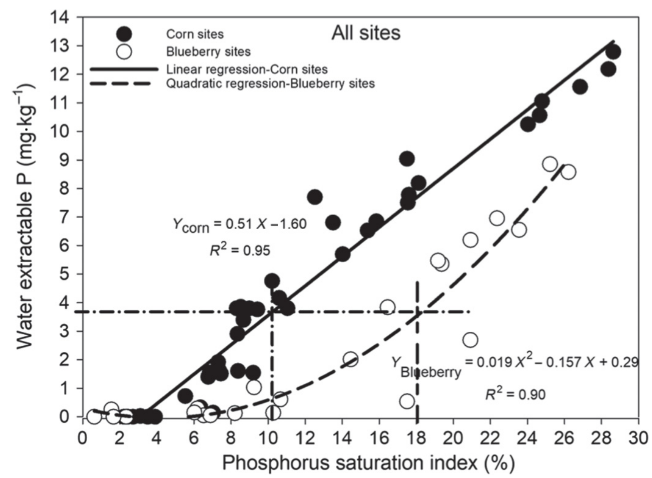


Fig. 4. Relationships between phosphorus (P) saturation index and water-extractable P for silage corn (median soil pH = 5.5) and blueberry sites (median soil pH = 5.5) in south coastal British Columbia.



variables analyzed, Al and OM content had the greatest influence on P sorption for the studied soils. The S_{max} values of the eight soils were in the range of those presented in other studies (Messiga et al. 2011; Wang et al. 2012). However, the wide range of S_{max} observed indicates differences among soils in their capacity to retain or fix newly applied P from fertilizer and manure. The Pearson's correlation coefficient between the S_{max} and

Fig. 5. Phosphorus (P) saturation index vs. measured or simulated water-extractable P for (*a*) silage corn sites (median soil pH = 5.5) and (*b*) blueberry sites (median soil pH = 5.5) in south coastal British Columbia.

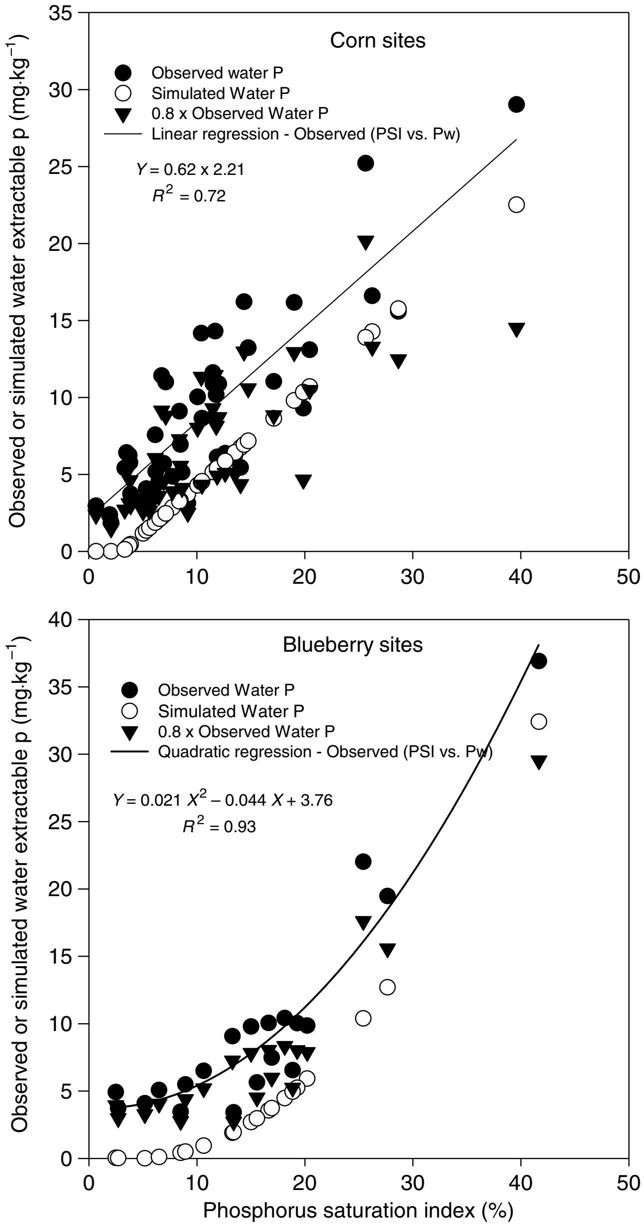
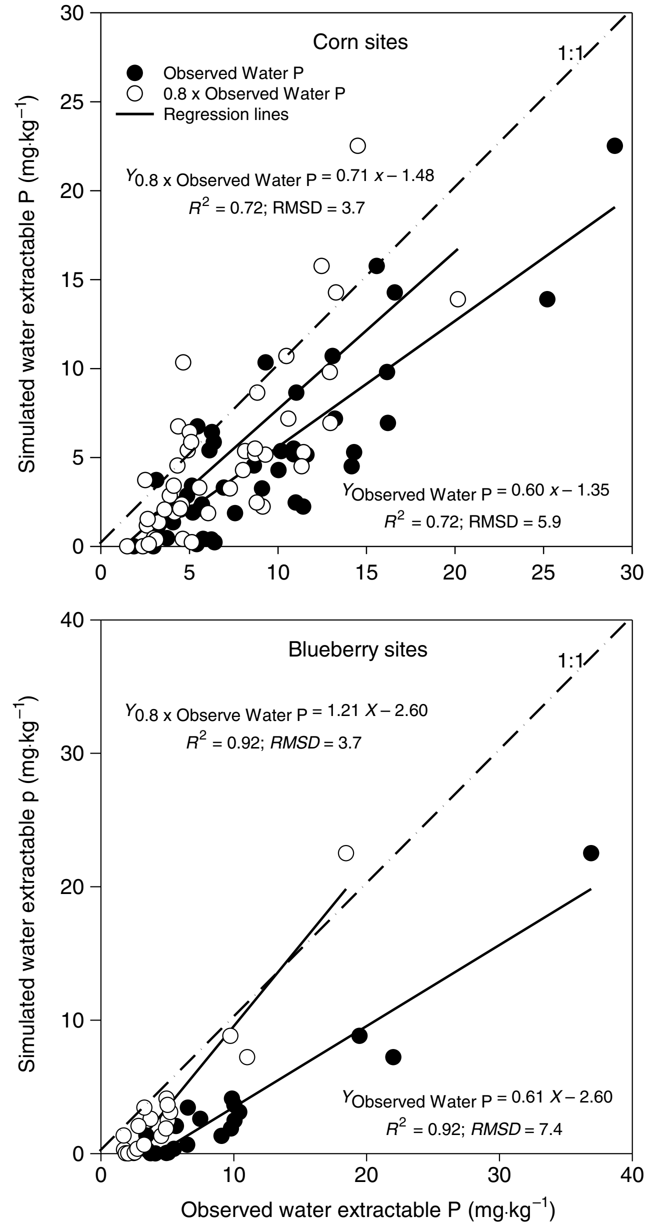


Fig. 6. Measured vs. simulated water-extractable phosphorus (P) for (*a*) silage corn sites (median soil pH = 5.5) and (*b*) blueberry sites (median soil pH = 5.5) in south coastal British Columbia.



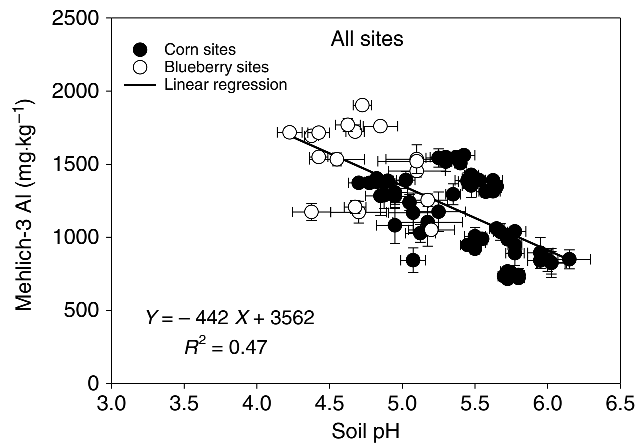
Al_{M3} was 0.46, and the Pearson's correlation coefficient between the S_{max} and OM content was 0.59 (Table 3). The close association between S_{max} and Al is further highlighted by the significant and positive correlation between S_{max} and PSC ($Al_{Ox} + Fe_{Ox}$) confirming the role of Al and Fe oxyhydroxides on P sorption characteristics (Table 3). Yan et al. (2013) used a path analysis (a form of multiple regression used to evaluate causal models) to partition Pearson's correlation coefficients into direct and indirect effects, and their results showed that Al_{Ox} had a significant direct effect on S_{max}, whereas the direct effects of Fe_{Ox}, OM content, and pH on S_{max} were not significant. The authors concluded that Al_{Ox} was a dominant contributor to S_{max} compared with other soil properties (Yan et al. 2013). In the present study, a positive correlation between OM content and S_{max} could be partly explained by the use of solid manure by dairy farmers as source of nutrients. In a previous study assessing the sorption characteristics of aggregate size particles from no-till and conventional till soils, we discussed three mechanisms through which OM influences S_{max} (Messiga et al. 2011). Some mechanisms decrease soil P sorption capacity due to direct competition between organic molecules and ligand exchange sites that would otherwise precipitate P (Messiga et al. 2011).

Critical agri-environmental P indicators

The PSC provides an approximation of the quantity of sorption sites in soils available to fix newly applied P (Renneson et al. 2015). A soil with saturated PSC easily releases P to plants during the growing season but also retains less P following rainfall or snowmelt events as they occur during the non-growing season in south coastal BC. The significant relationship ($P < 0.001$) and R^2 of 0.85 demonstrate that DPS can be used to predict Pw values across silage corn and blueberry production systems in south coastal BC. Similar relations describing how DPS relates to Pw were obtained across a wide range of soil types in other regions (Pellerin et al. 2006; Renneson et al. 2015; Benjannet et al. 2018). The average critical Pw of 3.7 mg·kg^{-1} (DPS = 25%) obtained in the present study is close to the environmental threshold of 4.0 mg·kg^{-1} across Canadian farmlands suggested by van Bochove et al. (2012), but it is lower than the 9.7 mg·kg^{-1} suggested for soils from Quebec (Pellerin et al. 2006) and the Atlantic provinces of Canada (Benjannet et al. 2018). The method described by Self-Davis was used in the present study and that of van Bochove et al. (2012). The method described by Sissingh (1971) was used by Pellerin et al. (2006) and Benjannet et al. (2018), which likely explains the large difference between Pw concentrations. The Self-Davis method uses a water:soil extraction ratio of 10:1 and shaking time of 1 h, whereas the Sissingh method uses a water:soil extraction ratio of 60:1 and a shaking time of 22 h.

The primary focus of this study was to understand how PSI relates to well-established and widespread environmental indicators such as DPS and Pw in acid to slightly-acid soils of south coastal BC. Two regressions with average R^2 of 0.84 described the relationships between DPS and PSI, one for the silage corn sites and the other for the blueberry sites (Fig. 3). Similarly, two regressions described the relationships between Pw concentrations and PSI, one for the silage corn sites, with R^2 of 0.95, and the other for the blueberry sites, with R^2 of 0.90 (Fig. 4). Interestingly, the critical Pw concentrations of 3.7 mg·kg^{-1} corresponded to critical PSI values of 10.4% for the silage corn sites and 18.0% for the blueberry sites (Fig. 4). These critical PSI values suggest that the risk of P transport by runoff is high at PSI > 10.4% for silage corn fields and PSI > 18.0% for blueberry fields. The silage corn sites differed from the blueberry sites mainly in their soil pH. Descriptive statistics of soil pH values showed that median soil pH was 5.5 (25% percentile = 5.08 and 75% percentile = 5.72) across the silage corn sites and 4.7 (25% percentile = 4.42 and 75% percentile = 5.1) across the blueberry sites (Fig. 5). In a recent study, Penn et al. (2018) showed that P_{M3} extraction is decreased with increasing soil pH, partially because of changes in P forms, partial neutralization of extractant pH, and consumption of extractant fluoride by non-P-containing calcium minerals. We found that the occurrence of low pH was also associated with increased Al_{M3} concentrations (Fig. 7), which is consistent with other studies (Benjannet et al. 2018). It is, therefore, possible that at low soil pH, Mehlich-3 extraction solution targets forms of P associated with non-oxyhydroxide Al, which overestimates the solubility of labile P. This would explain the higher threshold of critical PSI in the blueberry sites compared with the silage corn sites (Fig. 4). The combination of critical PSI and Pw concentrations as agri-environmental indicators represents an improvement in the way the risk of P loss is assessed among production systems in south coastal BC. The PSI alone can overestimate the risk of P loss to the environment, but coupled with soil pH or Pw, it provides an assessment of the environmental risk of the soil. In silage corn sites, application of manure and supplement of starter fertilizer blends as the main source of N has little effects on the acidity of the soil (Zhang et al. 2018; Messiga et al. 2020). Lower soil pH, in the blueberry sites compared with the silage corn sites is due to the use of ammonium sulfate and other acidifying N fertilizers by local farmers as source of N to inhibit the nitrification process because blueberry plants preferentially absorb ammonium over nitrate (Messiga et al. 2018). Low soil pH also prevails in newly established and young blueberry fields because elemental sulfur is applied to the soil at establishment to decrease the pH, as blueberry plants grow best when soil pH is between 4.2 and 5.5 (Poonnachit and Darnell 2004). The majority of soils under blueberry sites used in the present study had pH values below 5.1 (75% percentile), but in line with the literature a cut-off pH of 5.5 could be used to differentiate silage corn and blueberry sites. Additional studies using soils collected from blueberry sites will be needed to assess these relationships

Fig. 7. Relationship between soil pH and Mehlich-3-extractable aluminum for silage corn (median soil pH = 5.5) and blueberry sites (median soil pH = 5.5) in south coastal British Columbia.



over the entire range of pH (4.2 and 5.5) prevailing in this perennial cropping system. The literature shows that soils with a range of pH as observed in the present study can be divided into two classes according to their P solubility when extracted with Mehlich-3 solution: high solubility with soil pH <5.5; low solubility with soil pH >5.5 (Benjannet et al. 2018; Penn et al. 2018).

Validation of critical Pw value

The simulations mimicked the trends of Pw concentrations for all soils across the two production systems (Figs. 5*a*, 5*b*). These results further support the recommendation of two regressions to describe how PSI relates to Pw concentrations in silage corn and blueberry production systems as influenced by soil pH (Benjannet et al. 2018; Penn et al. 2018). However, observed Pw concentrations were on average larger than simulated values, and RMSD values of 5.9 for silage corn sites and 7.4 for blueberry sites were large enough to indicate a significant mismatch between simulated and observed Pw concentrations (Figs. 6*a*, 6*b*). One possible reason for this mismatch is that Pw concentrations in soil extracts from the 2005 soil survey were analyzed by ICP, whereas Pw concentrations in soil extracts for the current study were analyzed by the colorimetric method (Murphy and Riley 1962). The literature shows that Pw concentrations determined by ICP are significantly higher than those determined by colorimetric, and the differences are due to the presence of organic P (Adesanwo et al. 2013). To improve the simulations, we considered a scenario with a ratio of 0.8 (80%) between Pw measured by ICP and Pw measured by colorimetric. Accordingly, Pw concentrations obtained in the 2005 soil survey were multiplied by 0.8 (0.8 × observed Pw concentrations) and plotted against simulated Pw concentrations. The mismatch between simulated and observed values were lessened by considering a 0.8 factor, and RMSD value was on average 3.7 for the two cropping systems. These simulations could be improved by testing additional scenarios because the slope of the regression was 0.71 for corn sites and 1.21 for blueberry sites (Figs. 6*a*, 6*b*). However, we anticipate that other factors could affect the outputs of the simulations. For example, differences in OM content among soils from the 2005 survey indicate that different ratios, one for each soil, should be used to transform Pw data obtained by ICP. Soil texture is another factor that could affect the output of the simulations and therefore should be accounted for in the grouping of soils. For future work, training and validation Pw concentrations should be obtained using standard methods.

Agronomic and environmental implications for soils with high-legacy P

The PSI is used in acid soils in several Canadian provinces (Sims et al. 2002; Pellerin et al. 2006; Wang et al. 2012; Benjannet et al. 2018). This work is, to our knowledge, the first attempt in south coastal BC to relate PSI and Pw concentrations in two major production systems, silage corn (median soil pH >5.5) and blueberry (median soil pH <5.5), with the goal of defining a critical P risk indicator.

Two critical PSI values were obtained from the present study, 10.5% for the silage corn sites and 18% for the blueberry sites. These values correspond to a critical Pw concentrations of 3.7 mg·kg^{-1} across the two cropping systems. Above these critical PSI and Pw concentrations, offsite transport of P in surface or subsurface runoff will likely increase. For soils with PSI below critical values, annual P inputs should be planned to maintain agronomical soil P levels. For soils with PSI above critical values, annual P inputs should be less than outputs, and reliance for plant P nutrition should be placed on legacy soil P. For silage corn, one strategy will consist of limiting the use of starter fertilizer P; another strategy is to find ways to adequately address dairy manure application, which is the biggest constraint because of high animal stocking densities in south coastal BC (Reid and Schneider 2019). We recently demonstrated that P fertilizer recommendations for silage corn can be refined by decreasing starter P rates to "5.0 to 7.5" kg P·ha^{-1} without decreasing dry matter yield at harvest (Messiga et al. 2020). For blueberry production systems, there is a need for scientific evidence on optimum P fertilizer rates to refine actual fertilizer P recommendations. Over a 6 yr study conducted in Prince Edward Island, Canada, plant growth and berry yields of wild blueberry were not affected by rate of soil applied P fertilizer even in soil with low soil test P (Sanderson and Eaton 2008). Another study conducted in Saguenay-Lac-Saint-Jean (Quebec, Canada) between 2009 and 2012 showed a marginal positive effect of P fertilization on berry yield of wild blueberry (Lafond 2020). These studies refer to wild and lowbush blueberries, which may not be relevant for highbush blueberries found in BC. Therefore, additional work is needed to refine P fertilizer recommendations for highbush blueberries.

Conclusions

The S_{max} values varied widely among soils and were influenced by Al and OM content. The close association between S_{max} and Al implies that Al oxyhydroxides play a dominant role on soil P fixation in south coastal BC. Increased OM content in soils with high S_{max} values could be explained by solid manure applications, but the contrasting effects of organic molecules derived from OM on P sorption make it difficult to rule on the resulting effects on P fixation in these soils. The critical PSI values were 10.4% for the silage corn sites and 18% for the blueberry sites, and these values corresponded with a critical Pw value of 3.7 mg·kg^{-1}. The PSI alone can overestimate the risk of P loss to the environment, but coupled with soil pH or Pw concentrations, it provides an assessment of the environmental risk of the soil. The combination of critical PSI and Pw concentrations as agri-environmental indicators represents an improvement in the way the risk of P loss is assessed among production systems in south coastal BC. The different PSI values between the two production systems are mainly due to differences in soil pH, with silage corn sites exhibiting soil pH >5.5, whereas blueberry sites were characterized by soil pH <4.7. The descriptive capability of the regressions used to derive critical PSI and Pw concentrations was successful when tested using archive soil data from five soil types under corn–grass systems and three soil types under blueberry production systems across south coastal BC. Our research has contributed to the understanding and use of indicators that could be used to monitor and assess the environmental risk of P for silage corn and blueberry production systems in high-legacy P soils of south coastal BC.

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