Computers and Electronics in Agriculture 206 (2023) 107672

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Modification of the RZWQM2-P model to simulate labile and total phosphorus in an irrigated and manure-amended cropland soil

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ARTICLE INFO

Keywords:
Soil P modeling
RZWQM2-P
Manure management
Crop rotation
Soil recovery

ABSTRACT

With the expansion of the dairy industry, phosphorus (P)-enriched dairy manure has increasingly been used to replace chemical fertilizer to meet crop nutrient demand. This practice could lead to excessive total P accumulation in the soil and increase the risk of P pollution in the environment. The newly-developed RZWQM2-P model uses the soil P pool structure from the EPIC model, which is not sensitive to total soil P. Therefore, we modified the P module in RZWQM2-P to improve its capability in simulating total soil P. We subsequently assessed the ability of the modified model to simulate labile soil P, total soil P, plant P uptake, and crop yield using a dataset collected from an irrigated field treated with dairy manure and inorganic fertilizer at eight rates under a repeating wheat-potato-barley-sugar beet rotation. The results suggested that the modified RZWQM2-P model satisfactorily simulated field-measured annual total soil P, plant P uptake, and crop yield. Labile soil P was simulated less accurately, but the results were acceptable as the model responded well to P treatments. We simulated the long-term soil P dynamics under three P-application scenarios. Long-term simulation results showed that it took 14 years for the labile soil P level to return to the initial level after eight years of manure-P applications at a rate of 65.5 kg P/ha year^{-1}. The modified RZWQM2-P model can be used to simulate total soil P and labile soil P contents and to assess P management practices in irrigated cropland amended with manure.

1. Introduction

The dairy industry is expected to grow continuously in order to supply the increasing protein demand to feed world population (Hill et al., 2021). Idaho has the third-largest dairy-industry in the United States (Lauer et al., 2018). Development of the dairy industry has promoted the local economy, but has also been the source of environmental problems, including waste disposal (Cabrera et al., 2009). As a result, dairy manure has increasingly been used to replace chemical fertilizer as a source of nutrients to meet crop growth requirements for nitrogen (N) and phosphorus (P) due to the expansion of the milk-producing industry in southern Idaho (Leytem et al., 2011). This practice recycles nutrients and waste from animal feeding and enhance soil fertility, but it may lead to P accumulation in the soil and become non-point source pollution for aquatic systems (Obi and Ebo, 1995; Wang et al., 1996; Weyers et al., 2016). Of the P used in crop production, only about 20 % is assimilated by plants (Cordell et al., 2009). Therefore, rationally managing P applications through manure and fertilizer is crucial for saving P resources, maintaining soil health, and reducing agricultural pollution. In addition, evaluating the impact of long-term high fertilization application rates on soil P dynamics would facilitate the determination of fertilization strategy (e.g. fertilizer application rates) (Chen et al., 2022). However, field research on nutrient reduction strategies has been limited to a narrow range of time periods, soil types, and specific treatments (Craft et al., 2018; Tuppad et al., 2010). Agricultural modeling tools can investigate the effects of high fertilization rates on soil P dynamics by extending results beyond the constraints of field research.

The Root Zone Water Quality Model 2 (RZWQM2) is a one-dimensional field-scale agricultural model that integrates physical, chemical, biological, and hydrological processes (Ahuja et al., 2000). RZWQM2 has been used world-wide to study hydrology, nutrient dynamics, crop growth, and greenhouse gas emissions (Jiang et al., 2018; Liu et al., 2017; Ma et al., 2007; Qi et al., 2012). A P module was recently developed using the P framework in the EPIC model (Jones et al., 1984) and the most recently updated science regarding P cycling (i.e., Vadas, 2014). This P module was subsequently incorporated into RZWQM2 to

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https://doi.org/10.1016/j.compag.2023.107672
Received 15 September 2022; Received in revised form 28 December 2022; Accepted 20 January 2023
Available online 7 February 2023

Table 1
Crop management inputs for the RZWQM2 scenarios.

Year	Crop	Planting date	Density plants (ha^{-1})	Row spacing (cm)	Harvest date
2013	Spring wheat	02 April	2,209,000	18	13 August
2014	Potato	29 April	35,625	91	10 September
2015	Spring barley	31 March	2,209,000	18	29 July
2016	Sugar beet	09 May	82,200	22	11 October
2017	Spring wheat	05 April	2,209,000	18	15 August

create the RZWQM2-P model that simulates P dynamics in soil, plant, and water (Sadhukhan et al., 2019a). RZWQM2-P has been successfully used to predict the loss of different P forms, including dissolved reactive P, particulate P. and total P, through tile drainage flow in subhumid regions (Sadhukhan et al., 2019b). However, the EPIC model P framework, widely adopted in many P models, was not designed to address the dynamics of total P in the soil. Therefore, the first objective of this study was to improve RZWQM2-P's capability in simulating the dynamics of total P in the soil by modifying the EPIC P framework. In addition, RZWQM2-P has never been used to predict soil P dynamics (i.e., labile and total P) in irrigated agriculture in which P-management practices urgently need to be assessed. Hence, the second objective was to evaluate the modified RZWQM2-P model using labile soil P and total soil P (hereafter referred to as simply labile P and total P) data collected from an irrigated field amended with various P fertilization rates, and then to quantify soil P recovery behaviour under different P-management strategies.

2. Materials and methods

2.1. Field experiment

The experimental data used to assess RZWQM2-P were collected from a field located at the USDA-ARS Northwest Irrigation and Soils Research Laboratory farm near Kimberly, Idaho, USA (lat. 42° 33′ N, long. 114° 21′ W). The field experiment started in the fall of 2012 and had a repeating four-year crop rotation of spring wheat (*Triticum*

Table 2
Manure application time, rate, and properties. "A" represents manure applied on an annual basis (once in a year) and "B" represents manure applied on a biennial basis (once in two years).

Treatment	Application date		Manure rate	Manure properties				
			$kg\ ha^{-1}$	Total P $kg\ ha^{-1}$	Total N $kg\ ha^{-1}$	NH_4^+-N $kg\ ha^{-1}$	C:N -	Fraction of C -
Manure_18TA	2013	6-Nov	22,587	140	420.12	64.08	17.45	0.325
	2014	23-Oct	20,000	67	196.86	43.78	15.61	0.181
	2015	22-Oct	19,000	128	267.99	52.64	14.54	0.21
	2016	16-Nov	17,248	96	281.12	60.48	14.8	0.187
Manure_18TB	2014	23-Oct	16,970	67	232.15	37.12	15.13	0.159
	2016	16-Nov	17,248	125	281.12	60.48	15.8	0.212
Manure_36TA	2013	6-Nov	44,000	265	809.84	124.78	16.97	0.312
	2014	23-Oct	41,000	139	478.25	88.66	15.79	0.187
	2015	22-Oct	39,000	258	563.28	106.4	14.16	0.204
	2016	16-Nov	34,720	251	566.72	122.08	16.1	0.192
Manure_36TB	2014	23-Oct	36,640	139	432.35	88.66	15.79	0.187
	2016	16-Nov	34,720	251	566.72	122.08	16.2	0.199
Manure_52TA	2013	6-Nov	70,000	423	1298.15	199.07	16.63	0.308
	2014	23-Oct	55,494	203	699.22	121.39	15.79	0.199
	2015	22-Oct	58,000	386	829.76	160.16	15.07	0.217
	2016	16-Nov	51,968	376	848.96	183.68	15.9	0.191
Manure_52TB	2014	23-Oct	58,000	203	728.19	126.42	16.14	0.214
	2016	16-Nov	51,968	376	848.96	183.68	14.8	0.194

Manure treatment codes are defined in section 2.1.

Table 3
Inorganic fertilizer (N and P) application times and rates.

Year	Crop	Applied date	Manure_18TA $kg\ ha^{-1}$	Manure_18TB $kg\ ha^{-1}$	Manure_36TA $kg\ ha^{-1}$	Manure_36TB $kg\ ha^{-1}$	Manure_52TA $kg\ ha^{-1}$	Manure_52TB $kg\ ha^{-1}$	Fertilizer $kg\ ha^{-1}$
					Inorganic Nitrogen				
2013	spring wheat	04 April	43.46	43.46	43.46	43.46	43.46	43.46	43.46
2014	potato	16 April	112.00	84.00	84.00	112.00	84.00	112.00	84.00
		20 May	112.00	134.40	89.60	134.40	89.60	112.00	134.40
		24 July	44.80	44.80	44.80	44.80	44.80	44.80	44.80
2015	spring barley	31 March	–	–	–	–	–	–	53.76
2016	sugar beet	20 April	31.36	123.20	–	40.32	–	–	123.20
2017	spring wheat	04 April	10.80	52.64					107.88
					Inorganic Phosphorus				
2013	spring wheat	04 April	–	–	–	–	–	–	40.00
2014	potato	16 April	–	–	–	–	–	–	89.00
		20 May	10.00	67.50	–	–	–	–	–
		24 July	–	–	–	–	–	–	–
2015	spring barley	31 March	–	–	–	–	–	–	20.00
2016	sugar beet	20 April	–	–	–	–	–	–	–
2017	spring wheat	04 April	–	–	–	–	–	–	19.00

"–" indicates no corresponding nutrient applied. Manure treatment codes are defined in section 2.1.

aestivum L., 2013, 2017)-potato (*Solanum tuberosum* L., 2014)-spring barley (*Hordeum vulgare L.*, 2015)-sugar beet (*Beta vulagaris* L., 2016). Crop management parameters are given in Table 1.

The experiment was laid out as a completely randomized block design with individual plot size of 12.2 m × 18.3 m. There were eight treatments replicated four times. The treatments included no chemical fertilizer or manure (Control), chemical fertilizer only (Fertilizer), solid dairy manure applied annually at three specific rates (Manure_18TA, Manure_36TA, and Manre_52TA, where the digits followed by "T" represent the manure rate (tons ha^{-1}), for example 18 T presents approximately 18 tons ha^{-1} manure used in the treatment, and "A" represents "Annually"), and solid dairy manure applied biennially at the same three rates (Manure_18TB, Manure_36TB, and Manure_52TB, where "B" represents "Biennially"). In order to maximize crop yield, chemical fertilizer was also applied to some of the manure plots in some years as would be done by commercial growers (Koehn et al., 2021). Details regarding manure and inorganic fertilizer applications are given in Tables 2 and 3, respectively. Manure was incorporated into the soil by disking immediately after application; the Fertilizer and Control treatments were also disked at the same time. All treatments were irrigated using sprinklers with application amounts of 41.1 cm for wheat in 2013, 59.3 cm for potato in 2014, 34.2 cm for barley in 2015, 72.6 cm for sugar beet in 2016, and 57.4 cm for wheat in 2017.

The soil was a Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids; USDA-NRCS, 2016). Soil samples were collected each fall (Sep. 25–26, 2012; Sep. 30, 2013; Oct. 9, 2014; Sep. 24, 2015; Nov. 15, 2016; and Sep. 18, 2017) before treatment application to a depth of 122 cm using a hydraulic soil probe (9100 Ag Probe, AMS Inc. American Falls, ID). Three cores were collected per plot and separated into five segments (0–15, 15–30, 31–60, 61–91, and 92–122 cm) then composited, airdried and ground to pass a 2 mm sieve prior to analysis of bicarbonate extractable (Olsen P) and total P. Olsen-P was analyzed for soil sampled in all years, while total P was only analyzed for soils in 2013, 2014, and 2017. To measure Olsen-P, 5-g soil samples were shaken with extractant (0.5 M $NaHCO_3$) and then filtered through Whatman filter paper #42 (GE Healthcare UK ltd, Little Chalfont, UK; Olsen et al., 1954). Phosphorus in the extracts obtained from the Olsen-P method was determined by the ascorbic acid colorimetric method (Frank et al., 1998; Murphy and Riley, 1962) using a Skalar spectrophotometer (Skalar Analytical B.V., Breda, Netherlands). For analyzing total P, 0.25-g dried soil samples were digested by microwave-assisted digestion using concentrated H_2SO_4 and HCl, and with 30 % H_2O_2 added to aid in complete oxidation of organic matter. Total P was determined by ICP-OES (PerkinElmer Optima 4300 DV, Wellesley, MA) detection (US-EPA, 1996).

Wheat and barley yields were determined by harvesting a 26 m^2 area with an Almaco plot harvester (1.5-m header) followed by bulk harvesting of the field after which the straw was swathed and baled and removed from the field. Potato tuber yield was determined for each plot using a single row potato digger (Grimme, Lincolnshire, UK) with 33.5 m of row within each plot. Following plot harvest the field was bulk harvested by a commercial operator. Sugar beet yield was determined by mechanically harvesting 21 m of row with a two-row beet harvester, after which bulk harvest was completed. Total P was determined in plant samples by digesting 0.5-g dried sample with concentrated HNO_3 and HCl, with 30 % H_2O_2 added, and the same microwave-assisted digestion method for soil total P (see above) was used to measure plant P uptake.

2.2. Model description and modification

RZWQM2 is a one-dimensional process-based model that integrates physical, biological, chemical, and hydrological processes in agricultural production systems (Ahuja et al., 2000). It has been widely used to study hydrology, water quality, crop growth, and nutrient transport (Liu et al., 2017; Ma et al., 2007; Qi et al., 2012; Sadhukhan et al., 2019b). RZWQM2 employs the Brooks-Corey equation (Brooks and Corey, 1964) for the soil water retention curve. Infiltration is described by the Green-Ampt equation (Green and Ampt, 1911) when rainfall or irrigation occurs, and soil water redistribution is described by the Richards equation (Richards, 1931). Surface runoff occurs when the rainfall rate exceeds the infiltration rate, and sediment yield is calculated using the Universal Soil Loss Equation (Wischmeier and Smith, 1978). The DSSAT4.0 crop growth model (Jones et al., 2003) was incorporated into RZWQM2 for a better simulation of crop yield.

A phosphorus module was recently incorporated into RZWQM2 to create RZWQM2-P that simulates the fate and transport of P in the soil–plant-water system. Specifically, RZWQM2-P simulates dissolved and particulate P losses in tile drained fields (Sadhukhan et al., 2019a). RZWQM2-P includes five different soil P pools: labile P pool, active P pool, stable inorganic P pool, stable organic P pool, and fresh organic P pool. The P losses (including dissolve reactive P and particulate P) through runoff from soil and the plant P uptake subroutine was adopted from Neitsch et al. (2011). The P for plant growth can only be absorbed from the labile P pool. The delineation and dynamics of labile, organic, and inorganic soil P pools were adopted from the EPIC model by Jones et al. (1984), while P absorption, desorption, and decomposition rates for surface residue and manure were adopted from the SurPhos model by Vadas et al. (2006). The distribution method for manure P and fertilizer P in the soil profile came from Vadas et al. (2007) and Vadas (2014).

RZWQM2-P has shown to be effective in predicting dissolved and particulate P loss through tile drainage and runoff (Sadhukhan et al., 2019a; Sadhukhan et al., 2019b). However, it has not been tested for simulating labile and total P pools in the soil due to the lack of continuous measurements of those two soil P pools in most cases. Our preliminary test showed that when initializing P pools, the fixed ratio of stable inorganic and active inorganic P, set to a fixed value of four, as adopted from EPIC by Jones et al. (1984), would result in error in soil total P balance. This would explain why Jones et al. (1984) stated that the EPIC model "is insensitive to pool sizes of stable inorganic P and total soil P". Additionally, we found that the P stress method adopted from Neitsch et al. (2011) was not properly structured in the P module because no yield loss was observed when P stress existed. This deficiency was corrected in this study by modifying the stable to active inorganic P ratio and P stress index as shown below.

2.2.1. Stable and active inorganic P ratio

To correct the problem of P initialization, we changed the fixed ratio of four between stable and active inorganic P pools to a user-defined input parameter for each soil layer. Users can compute this ratio using the equations listed below:

$$Ratio = \frac{P_{inorg}^{stab}}{P_{act}} \tag{1}$$

Stable inorganic P can be computed as:

$$P_{inorg}^{stab} = P_{tot} - P_{lab} - P_{act} - P_{org}^{stab} - P_{org}^{frsh} \tag{2}$$

where P_{inorg}^{stab} is stable inorganic P; P_{tot} is total P; P_{lab} is labile P; P_{act} is active inorganic P; P_{org}^{stab} is stable organic P; P_{org}^{frsh} is fresh organic P. The units for all P pools are kg ha^{-1}.

In this equation, total P and labile P (in this case Olsen-P) were measured, and active inorganic P can be computed as:

$$P_{act} = P_{lab} \times \frac{1 - PSP}{PSP} \tag{3}$$

PSP is the P sorption coefficient (or P availability index, unitless) that can be computed as done by Vadas. (2014):

$$PSP = -0.045 \times Log(Clay) + 0.01 \times P_{lab} - 0.035 \times SoilOC + 0.43 \tag{4}$$

where Clay is the percent of clay in the soil (i.e., 20 % for a loam soil), SoilOC is the percent of soil organic carbon content (i.e., 1.50 % for a soil

Table 4
Input initial labile P and total P used for the scenarios in RZWQM2.

Soil layers cm	Manure_18TA kg ha^{-1}	Manure_18TB kg ha^{-1}	Manure_36TA kg ha^{-1}	Manure_36TB kg ha^{-1}	Manure_52TA kg ha^{-1}	Manure_52TB kg ha^{-1}	Control kg ha^{-1}	Fertilizer kg ha^{-1}
				Labile P (Olsen-P)				
0–15	51.71	75.98	84.39	110.08	157.94	124.00	34.34	41.30
15–30	12.23	15.88	11.90	14.83	19.19	16.65	9.58	8.81
30–60	7.29	8.55	10.40	9.67	8.36	9.29	7.70	6.22
60–90	8.51	9.19	34.63	14.66	7.23	14.46	13.49	10.43
90–120	13.31	10.83	23.77	18.03	11.55	14.24	9.80	13.38
120–154	37.10	19.91	27.89	44.53	38.03	26.23	26.32	36.37
Total	130.15	140.34	192.98	211.80	242.3	204.87	101.23	116.51
				Total P				
0–15	1419	1598	1525	1817	1784	2029	1440	1496
15–30	1356	1414	1390	1427	1435	1460	1348	1437
30–60	2556	2706	2787	2678	2402	2606	2483	2536
60–90	2836	2818	2897	2893	2783	2795	2827	2935
90–120	3052	3082	3121	3080	2957	3102	2981	3190
120–154	2880	2758	2754	3130	2683	2914	2802	2859
Total	14,099	14,376	14,474	15,025	14,044	14,906	13,881	14,453

18,36,52 indicate that the applied manure amounts were approximately equal to 18, 36, and 52 t ha^{-1} respectively; A and B indicate annual and biennial, respectively, applications of manure.

with medium soil organic carbon content). Stable organic P (P_{org}^{stab}) can be estimated using the total carbon and assumed C:P ratio of 100:

$$P_{org}^{stab} = \frac{0.58 \times (SOM/100) \times Soilmass}{100} \tag{5}$$

where SOM is % soil organic matter content and soil mass is the mass of soil in a soil layer (kg ha^{-1}).

2.2.2. Crop P stress

The original crop P stress algorithm adopted from the SWAT model (Neitsch et al., 2011) showed unstable simulated P stress values and was replaced with the following equation:

$$Pstress = \frac{Bio_{p,act}}{Bio_{p,opt}} \tag{6}$$

where,

$Bio_{p,act}$ is actual plant P uptake in one day (kg ha^{-1}),
$Bio_{p,opt}$ is the optimum mass of P that should be assimilated by plant biomass in that day (kg ha^{-1}).

When the calculation result of P stress = 1, then the actual plant uptake of P meets the potential plant P demand, and no P stress exists for plants; when 0 < P stress less than 1, actual uptake of plant P cannot meet the plant demand for P. In this study, this modified P model was used to simulate the distribution of different forms of P in the soil profile and plant uptake P.

2.3. Model initialization and partition of P pools

The RZWQM simulation scenarios used in this study were adopted from Koehn et al. (2021). The soil hydraulic parameters (e.g., saturated hydraulic conductivity (k_{sat}) and field capacity water content at 1/10 bar (FC10)) and other parameters affecting soil nitrogen dynamics (e.g.,

Table 5
Initial P pool partitions in the Manure_52TA and Control scenarios.

Soil depth cm	SOM %	PSP	P_{lab} kg ha^{-1}	P_{tot} kg ha^{-1}	P_{act} kg ha^{-1}	P_{inorg}^{stab} kg ha^{-1}	P_{org}^{stab} kg ha^{-1}	P_{org}^{frsh} kg ha^{-1}	$\frac{P_{inorg}^{stab}}{P_{act}}$ Ratio
				Manure_52TA					
0–15	1.6 %	0.39	157.94	1784	249.89	1189.14	167.04	20.00	4.76
15–30	1.3 %	0.32	19.19	1435	40.75	1220.28	154.69	0.00	29.94
30–60	0.8 %	0.32	8.36	2402	18.06	2187.66	187.57	0.00	121.13
60–90	0.4 %	0.33	7.23	2783	14.81	2663.71	97.44	0.00	179.85
90–122	0.4 %	0.34	11.55	2957	22.51	2823.18	99.88	0.00	125.41
122–154	0.1 %	0.36	38.03	2683	68.39	2554.36	22.09	0.00	37.35
				Control					
0–15	1.6 %	0.34	34.34	1440	66.43	1152.64	167.04	20.00	17.35
15–30	1.3 %	0.32	9.58	1348	20.78	1162.96	154.69	0.00	55.97
30–60	0.8 %	0.32	7.70	2483	16.65	2270.59	187.57	0.00	136.40
60–90	0.4 %	0.33	13.49	2827	27.45	2688.46	97.44	0.00	97.95
90–122	0.4 %	0.34	9.80	2981	19.14	2851.89	99.88	0.00	149.03
122–154	0.1 %	0.35	26.32	2802	47.85	2706.17	22.09	0.00	56.56
				Fertilizer					
0–15	1.6 %	0.34	41.30	1496	78.54	1189.59	167.04	20.00	15.15
15–30	1.3 %	0.32	8.81	1437	19.14	1253.95	154.69	0.00	65.51
30–60	0.8 %	0.32	6.22	2536	13.47	2328.84	187.57	0.00	172.90
60–90	0.4 %	0.33	10.43	2935	21.29	2805.34	97.44	0.00	131.75
90–122	0.4 %	0.34	13.38	3190	26.03	3050.52	99.88	0.00	117.21
122–154	0.1 %	0.36	36.37	2859	65.51	2734.56	22.09	0.00	41.74

SOM is soil organic matter; PSP is P sorption coefficient or P availability index; P_{lab} is labile P; P_{tot} is total P; P_{act} is active inorganic P; P_{inorg}^{stab} is stable inorganic P; P_{org}^{stab} is stable organic P; P_{org}^{frsh} is fresh organic P.

Table 6
Calibrated plant P parameters for wheat, barley, potato, and sugar beet, and plant biomass parameters for sugar beet used in RZWQM2.

Crop	Biomass P Fraction			P uptake distribution parameter
	Emergence	Maturity	50 % Maturity	
Spring wheat	0.024	0.0005	0.01	10
Potato	0.024	0.0005	0.005	10
Spring barley	0.024	0.007	0.02	15
Sugar beet	0.024	0.002	0.0025	15

Sugar beet parameters

DSSAT parameter	Sugar beet-SVRR1142E
P1	900
P2	0.001
P5	700
G2	100
G3	0.5
PHINT	37.5

Maximum plant height = 50 cm
Plant biomass at half of max height = 400 kg ha^{-1}

P1 = Thermal time from seedling emergence to the end of the juvenile phase (°C days).
P2 = Delay in development for each hour that daylength is>12.5 h (0–1).
P5 = Thermal time from silking to physiological maturity (°C days).
G2 = Leaf expansion rate during stage 3 (cm^2 cm^{-2} day^{-1}).
G3 = Root tuber growth rate (g/m^{-2}(−|-) day^{-1}).
PHINT = Phyllochron interval; the interval in thermal time (°C days) between successive leaf tip appearances.

organic matter, residue pools, and microbial population) remained unchanged. The measured P_{lab} (Olsen-P) and P_{tot} (total P) data in 2013 were used to initialize the soil P pools. Model input soil P data is presented in Table 4.

When setting initial soil P pools, initial P_{lab}, P_{org}^{stab}, P_{org}^{frsh}, and the ratio of stable to active inorganic P are required in the model interface. Firstly, observed P_{lab} values are input to the RZWQM2-P interface while keeping other initial P pools as zero. During model execution, P_{act} values are calculated according to equation (3). PSP will be computed by the model using SOC, soil clay content, and labile P in soil. The P_{act} calculation results can be found in the SoilP output file. Then users are required to calculate P_{org}^{stab} and P_{inorg}^{stab} using Eqs. (5) and (2). P in fresh organic matter (P_{org}^{frsh}) in the tillage depths can be computed using the mass of soil residue (usually a few tons ha^{-1}) multiplied by residue P content (usually 1/10 of N content or approximately 0.2 %). Finally, the model user needs to compute the ratio of stable to active inorganic P pools using equation (1) for each soil layer, and enter all required initial P data to the model through the interface. Table 5 presents the initial P pool partitions for the Manure_52TA, Control and Fertilizer treatments as an example.

The P simulation results can be found in the RZWQM2 output files. The P balance (including P input from manure, inorganic fertilizer, crop residue, P losses through water, and plant P uptake) is given on both a daily and an annual basis, while the P content in different P pools is only given on a daily basis and is presented layer by layer, meaning that the total amount of a specific P form (i.e., P_{lab}, P_{act}, P_{inorg}^{stab}, P_{org}^{stab}, and P_{org}^{frsh}) needs to be summed for each layer to obtain total P.

2.4. Model calibration and validation

Because soil P was measured annually from 2013 to 2017, and because there were eight treatments in this study, we used data from four treatments (Manure_18TA, Manure_18TB, Manure_36TA, and Manure_36TB) in all years for calibration. The remaining four treatments (Manure_52TA, Manure_52TB, Control, and Fertilizer) were used for validation, following the suggestion given by Ma et al. (2012) of using multiple treatments in multiple years for calibration. Usually, the plots with no or the least amount of nutrient and water stress should be used for calibration because the crops in these plots can reach the potential yields. In this study, irrigation depth and timing were the same for all plots, and the P application rates to all plots (except for the Control plots with no P applied, Tables 2 and 3) were sufficient for unstressed crop growth. Therefore, the treatments of Manure_18TA, Manure_18TB, Manure_36TA, and Manure_36TB were used to calibrate the model, while the data from Manure_52TA, Manure_52TB, Control, and Fertilizer were used for validation.

Soil and crop parameters related to phosphorus were calibrated against observed total P (P_{tot}), labile P (P_{lab}), and plant P uptake (P_{upt}) on top of the previous calibration for soil nitrogen by Koehn et al. (2021). The calibration was undertaken manually while changing the parameters within a reasonable range by a trial-and-error method following the protocol given by Ma et al. (2012) and repeated several times until a best match with the observed data was obtained. Soil P parameters, including replenishment, detachability, filtration, and extraction coefficient, used the model default values. The crop P parameters as shown in Table 6 were calibrated against crop P uptake data. In this study, the DSSAT sugar beet model in RZWQM2-P was used instead of the original HERMES sugar beet model used by Koehn et al. (2021) because at this time only the DSSAT sugar beet model was linked to the phosphorus module of RZWQM2-P. The crop growth parameters for DSSAT sugar beet were calibrated using the observed sugar beet biomass values (Table 6).

RZWQM2-P was evaluated using percentage bias (PBIAS) and coefficient of determination (R^2):

$$PBIAS = \frac{\sum_{i=1}^{n}(P_i - O_i) \times 100}{\sum_{i=1}^{n} O_i} \tag{7}$$

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \overline{P})^2}}\right] \tag{8}$$

where O_i is the observed value; P_i is the simulated value; $\overline{O}$ and $\overline{P}$ are the means of observed and simulated values, respectively; n is the total number of observations. PBIAS reflects whether the simulation results are greater or less than the observed data (Gupta Hoshin et al., 1999). Positive values indicate model overestimation bias, and negative values indicate model underestimation bias. R^2 reflects the degree of collinearity between simulated data and measured data (Moriasi et al., 2007). Moriasi et al. (2015) rated model performance as acceptable when |PBIAS| was within 30 % and $R^2 > 0.4$ for P; good when |PBIAS| was between 10 and 15 % and $0.60 \le R^2 \le 0.80$; and very good when |PBIAS| was between 0 and 10 % and $R^2 > 0.80$.

2.5. Model application

The calibrated and validated RZWQM2-P model was then used to simulate three long-term (24-year, 1993–2017) scenarios with the potato-barley-sugar beet-spring wheat rotation. Four long-term scenarios were designed (i.e., Continuous treatment, Recovery treatment, Control_LT treatment, and Fertilizer_LT treatment (note: LT indicates long-term)). For the continuous treatment, the Manure_52TA manure and fertilizer application rates (52 tons ha^{-1} manure that contained 376 kg P ha^{-1}P) was applied in each of the 24 years. For the recovery treatment, the Manure_52TA manure application rate was applied for eight years and then terminated so that there was no P input for the remaining 16 years. For the Fertilizer_LT treatment, only fertilizer P was applied following rates from validated Fertilizer scenario. For the Control_LT treatment, no P was applied to the field for 24 years, so only the initial P amount from the validated Control treatment was available to support simulated crop growth. The management practices (e.g. irrigation, manure, fertilizer and tillage) in corresponding 4-year scenarios

Table 7
RZWQM2-P model accuracy statistics for total P in 2014, 2017, and overall.

PBIAS								
Year	Calibration				Validation			
	Manure_18TA	Manure_18TB	Manure_36TA	Manure_36TB	Manure_52TA	Manure_52TB	Control	Fertilizer
2014	13.84 %	−3.59 %	−4.12 %	−1.29 %	−8.72 %	−2.49 %	−8.26 %	−0.79 %
2017	4.83 %	−14.59 %	12.74 %	−7.71 %	−15.24 %	−7.97 %	−15.54 %	−10.68 %
Overall	9.12 %	−9.42 %	−8.71 %	−4.63 %	−12.19 %	−5.35 %	−12.03 %	−5.97 %
				R^2				
2014	0.79	0.98	0.96	0.95	0.88	0.88	0.99	0.97
2017	0.87	0.99	0.99	0.98	0.84	0.87	0.99	0.97
Overall	0.81	0.94	0.94	0.95	0.83	0.87	0.97	0.94

were repeated for the long-term simulation. The goal of this model application was to determine how many years it would take for excess input P to dissipate in the soil after repeated high P applications of manure. Historical weather data from 1993 to 2016 were used in the model application.

3. Results and discussion

3.1. Total P in the soil profile

The model satisfactorily simulated P_{tot} in different soil layers (Table 7) as indicated by low PBIAS and high R^2 values for all treatments. For the four calibration treatments (Manure_18TA, Manure_18TB, Manure_36TA, and Manure_36TB), the overall model performance for simulating total P in all soil layers across all years fell in the "very good" category (|PBIAS| within 10 % and $R^2 > 0.8$). For the four validation treatments (Manure_52TA, Manure_52TB, Control, and Fertilizer), the overall model performance for Manure_52TB and Fertilizer was also "very good", with PBIAS within 6.0 % and $R^2 > 0.8$. The overall model performance for the Manure_52TA and Control treatments as "good", with PBIAS values of −12.19 % and 12.03 % respectively, and $R^2 > 0.8$. Generally, RZWQM2-P tended to underestimate P_{tot} in the soil (-8.72 % to −0.79 % underestimated in 2014 and −15.54 % to −7.71 % underestimated in 2017) except for the Manure_18TA treatment, where the model-simulated P_{tot} was 13.84 % higher than the observed value in 2014 and 4.76 % higher than observed in 2017. Using the early version of the model, the total P simulation was mainly unsatisfactorily (with PBIAS about ± 75 to 90 %, data not shown). It suggests that the modification of the model is necessary and effective.

The simulated soil profile P_{tot} in 2017 only changed in the top two soil layers rather than in the deep layers (Table A1) because in this study P was applied to the top three soil layers (0–60 cm) in the model, and for deeper soil layers there was no additional input or output. These results also suggested that the model did not simulate downward movement of soluble P from the topsoil layers with soil water, or that the downward P flux as a result of soil water movement below 30 cm in the soil profile was negligible in this field under semiarid climate, particularly when total P was several orders of magnitude greater than soluble or plant available P. The observed total P in the 0–122 cm soil profile ranged from 11,079 kg ha^{-1} in Control in 2013 to 14,267 kg ha^{-1} in Manure_52TA in 2017. Although downward movement of P was not measured, a previous study showed that the P flux to tile drainage in a sub-humid climate following an intensive P application was about 0.4 kg ha^{-1} (Zhang et al., 2017). However, the observed P_{tot} in deep soil layers in our study did not vary much over time, showing an average increase of only 6 %. Therefore, the modeling strategy used to simulate total P was successful even though the downward movement of soluble P needs further testing.

3.2. Plant available P in the soil profile

Table 8 shows four years (2014–2017) of statistical results for simulated P_{lab} overall and for individual soil layers. The overall model performance in simulating P_{lab} was acceptable (PBIAS within ± 30 % and $R^2 > 0.4$) for most treatments. For the calibration treatments, the annual P_{lab} simulation result for Manure_36TA was "very good", with PBIAS of −8.83 % from the observed value of 275 kg ha^{-1} and $R^2 = 0.84$. The annual simulated P_{lab} for Manure_18TB was 132 kg ha^{-1}, 18.39 % higher than the observed value. However, for treatment Manure_18TA, the PBIAS and R^2 values for P_{lab} simulation were 55.54 % and 0.07, respectively, versus 14.55 % and 0.37 for treatment Manure_36TB, and these statistics indicated unacceptable simulation performance according to Moriasi et al. (2015). For the validation treatments, the statistical results for Manure_52TA were "very good" (PBIAS within ± 10 % and $R^2 > 0.80$), and for the Manure_52TB and Control treatments the results were "satisfactory" (PBIAS within ± 30 % and $R^2 > 0.40$). The annual P_{lab} predictions had PBIAS of 8.24 % for the Fertilizer treatment. However, the R^2 value of 0.12 indicated that the simulation result was

Table 8
RZWQM2-P model accuracy statistics for labile P in 2014, 2015, 2016, and 2017, and overall soil labile P.

PBIAS								
Year	Calibration				Validation			
	Manure_18TA	Manure_18TB	Manure_36TA	Manure_36TB	Manure_52TA	Manure_52TB	Control	Fertilizer
2014	9.80 %	*38.11 %*	20.16 %	12.60 %	−8.44 %	21.61 %	7.89 %	18.73 %
2015	19.36 %	0.44 %	−20.72 %	−5.16 %	−25.12 %	*−50.80 %*	11.24 %	*32.94 %*
2016	*155.25 %*	*34.24 %*	−12.77 %	*33.36 %*	−6.79 %	−12.61 %	−1.79 %	4.00 %
2017	*67.95 %*	10.02 %	−9.44 %	22.61 %	−1.26 %	−21.90 %	−17.37 %	−16.83 %
Overall	*56.38 %*	18.39 %	−8.83 %	14.55 %	−9.90 %	−25.20 %	−0.63 %	8.24 %
				R^2				
2014	0.96	0.85	0.93	0.98	1.00	0.97	0.76	0.88
2015	*0.26*	0.94	0.76	0.93	0.85	0.92	*0.12*	0.49
2016	*0.15*	0.69	0.90	0.98	0.96	0.90	0.66	*0.01*
2017	*0.12*	0.67	0.88	0.98	0.82	0.98	0.41	*0.11*
Overall	*0.06*	0.40	0.84	*0.37*	0.87	0.45	0.41	*0.12*

Italics indicate "unsatisfactory" statistical results.

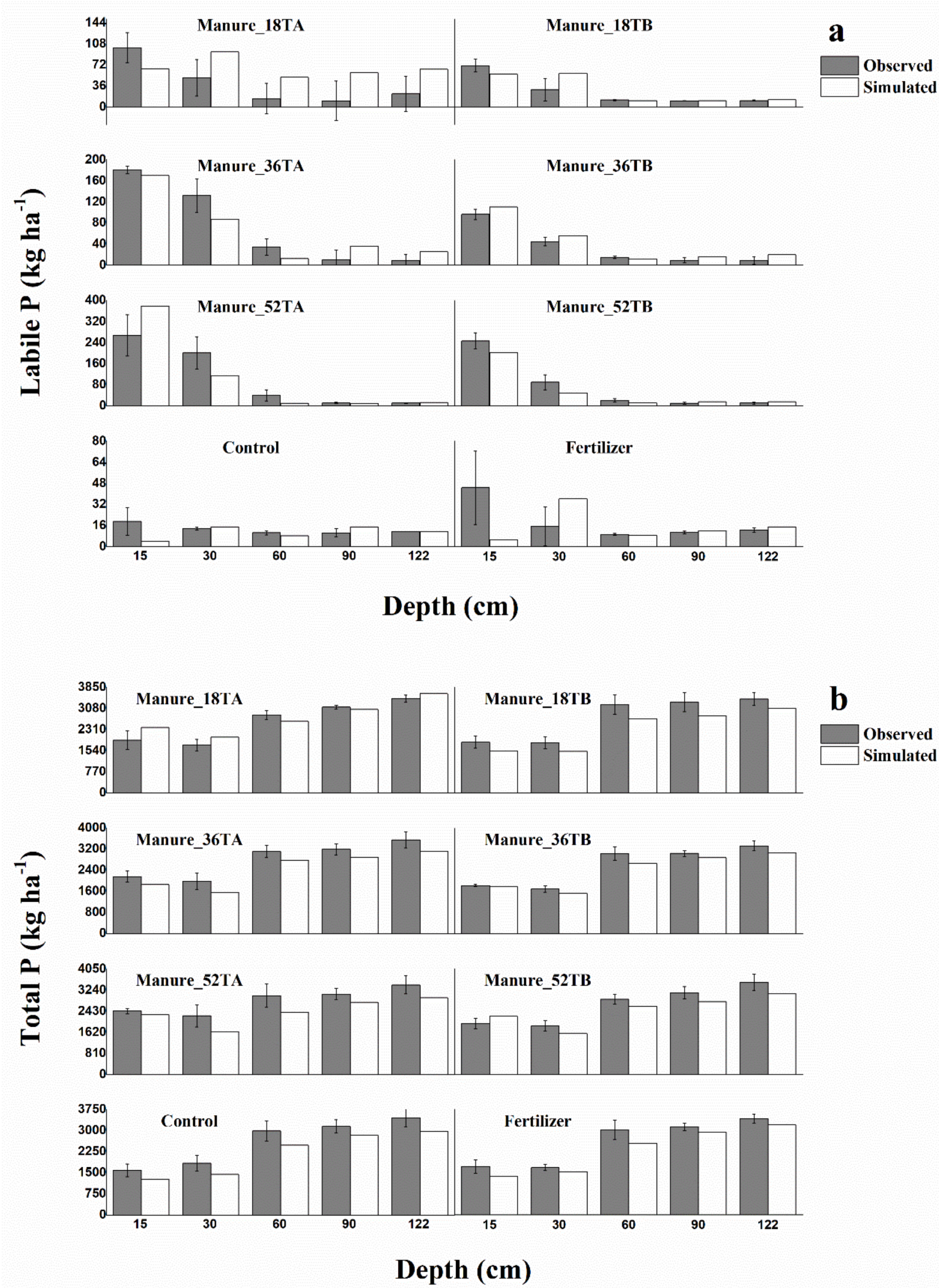

Fig. 1. Simulated and observed labile P (P_{lab}) (a) and total P(P_{tot})(b) on 18 September 2017 for eight fertilizer and manure treatments (treatment code definitions are given in Section 2.1).

Table 9
Simulated and observed plant P uptake, crop yield, and their model accuracy statistics for RZWQM2-P calibration and validation datasets.

Plant P uptake (kg ha^{-1})									
Year	Crop	Calibration				Validation			
		Manure_18TA	Manure_18TB	Manure_36TA	Manure_36TB	Manure_52TA	Manure_52TB	Control	Fertilizer
				Simulated					
2014	Potato	50.56	46.70	49.46	47.35	50.61	47.33	38.07	45.33
2015	Barley	71.21	96.38	64.33	66.18	60.20	63.74	79.75	85.09
2016	Sugar beet	62.95	64.71	66.08	63.13	66.05	63.03	49.10	65.03
Average		61.57	69.27	59.96	58.89	58.95	58.03	55.64	65.15
				Observed					
2014	Potato	44.01	44.32	46.46	42.06	51.82	49.04	40.96	42.33
2015	Barley	62.58	62.74	72.20	63.53	88.03	87.19	65.36	66.67
2016	Sugar beet	71.28	60.96	78.64	77.75	89.62	79.98	68.95	71.37
Average		59.29	56.01	65.77	61.11	76.49	72.07	58.42	60.13
PBIAS		3.85 %	23.68 %	−8.84 %	−3.64 %	−22.93 %	−19.47 %	−4.77 %	8.36 %
R^2		0.56	0.69	0.99	0.72	0.88	0.98	0.38	0.60
				Crop yield (kg ha^{-1})					
Year	Crop		Calibration				Validation		
		Manure_18TA	Manure_18TB	Manure_36TA	Manure_36TB	Manure_52TA	Manure_52TB	Control	Fertilizer
				Simulated					
2014	Potato	10,803	10,734	10,846	10,793	10,806	10,808	8335	10,428
2015	Barley	6961	9843	6245	6437	5827	6185	8477	8512
2016	Sugar beet	19,447	20,440	21,136	19,666	21,133	19,618	15,692	20,597
Average		12,404	13,672	12,742	12,299	12,589	12,203	10,835	13,179
				Observed					
2014	Potato	11,683	11,041	10,998	11,458	10,137	11,820	8473	11,514
2015	Barley	6659	6506	6349	6429	6015	5601	4694	6690
2016	Sugar beet	21,593	21,945	22,462	21,956	22,616	21,230	15,364	20,085
Average		13,312	13,164	13,270	13,281	12,923	12,884	9510	12,763
PBIAS		−6.82 %	3.86 %	−3.97 %	−7.40 %	−2.58 %	−5.28 %	13.93 %	3.26 %
R^2		1.00	0.95	1.00	1.00	0.99	1.00	0.87	0.95

Treatment code definitions are given in Section 2.1.

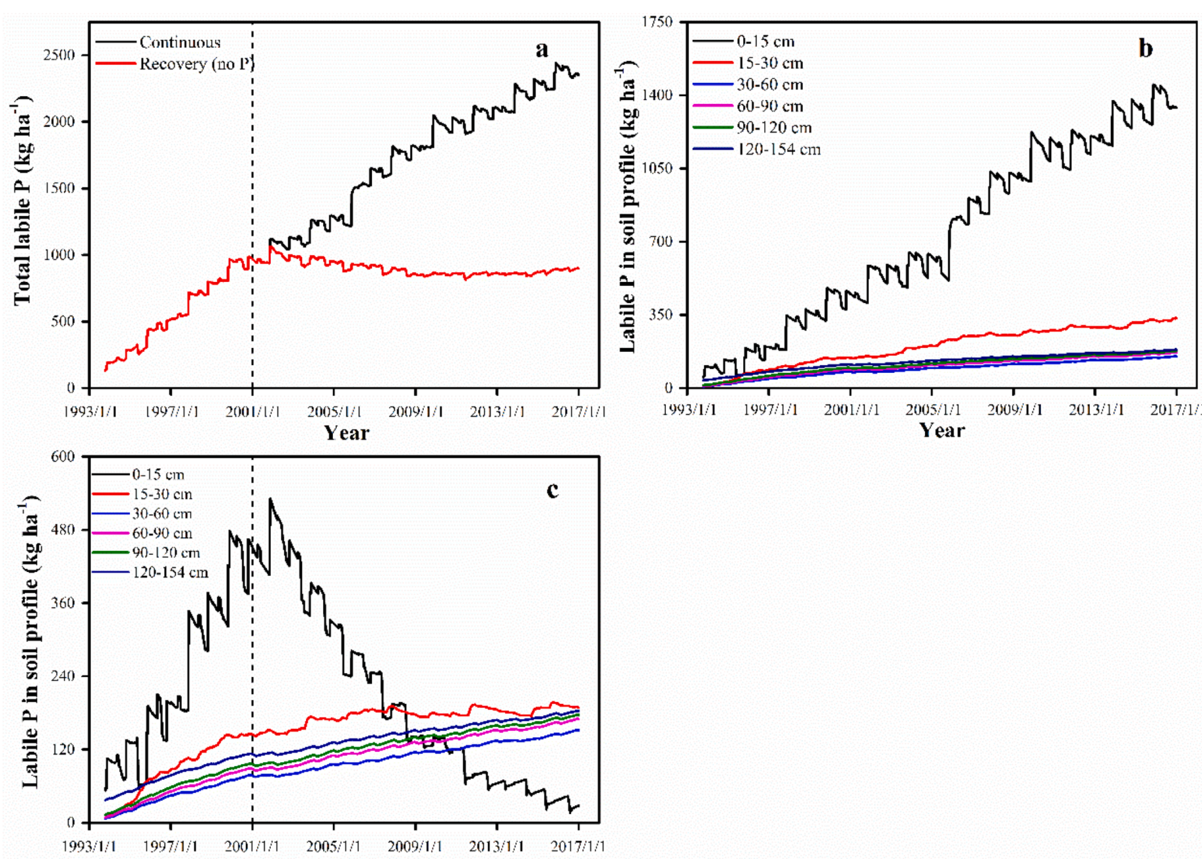

Fig. 2. Simulations of total labile P (P_{lab}) by RZWQM2-P over 24 years from all soil layers for Continuous and Recovery treatments (a), and P_{lab} contents in the soil profile in the Continuous treatment (b) and in the Recovery treatment (c). Dash line marks the year when manure application was stopped.

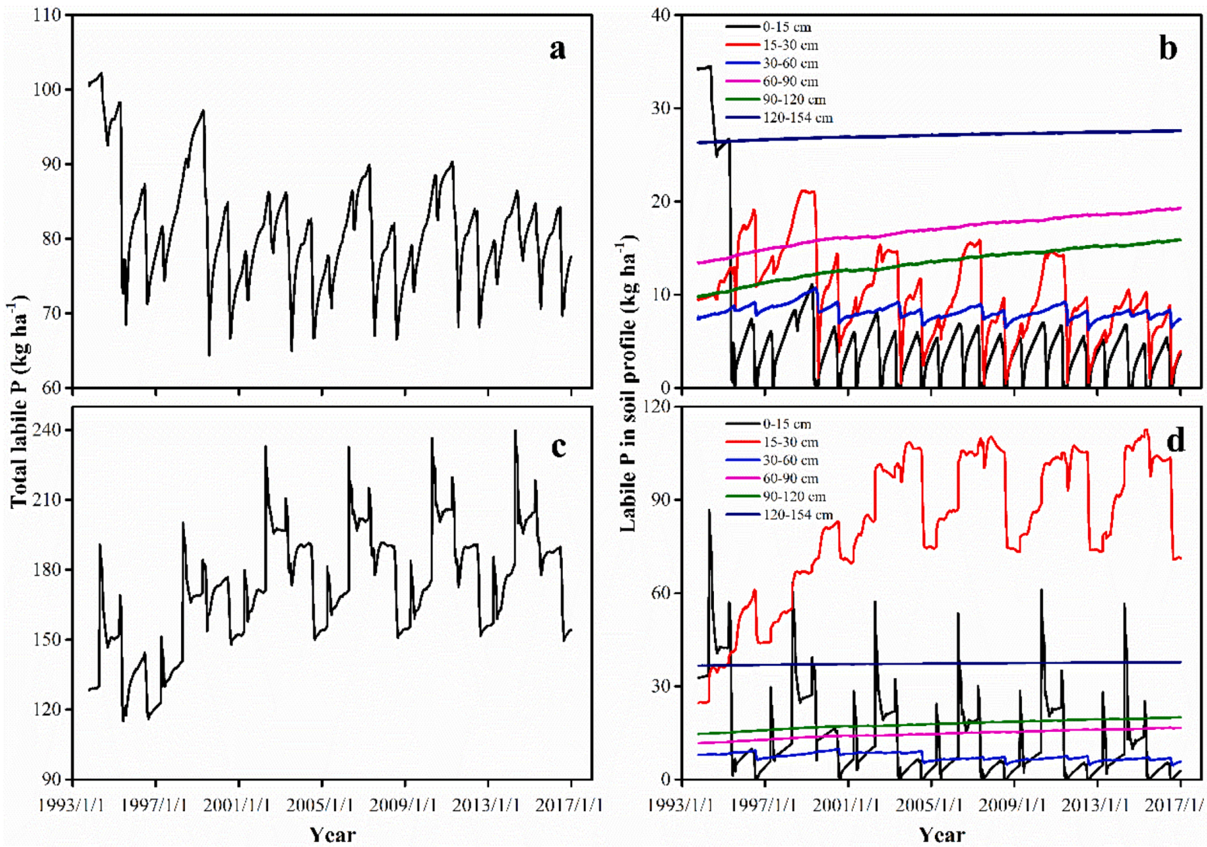

Fig. 3. Simulations of total labile P (P_{lab}) by RZWQM2-P over 24 years in the Control_LT treatment (a) and in the Fertilizer_LT treatment (b) from all soil layers, and P_{lab} content in six soil profile layers for the Control_LT treatment (c) and for the Fertilizer_LT treatment (d).

"unsatisfactory".

The data in Table 8 also suggest that the model performance is considered as acceptable because the PBIAS values are within ± 30 % in more than 78 % of the cases and $R^2 > 0.40$ in more than 80 % of the cases. The majority of the "unsatisfactory" simulation occurred in the Manure_18TA and Fertilizer treatments in which the P inputs were relatively low. For those no P and low P input treatments (i.e., Control and Fertilizer), the simulated labile P in the topsoil layer (0–15 cm) was significantly underestimated (Fig. 1). This was because P depletion in the model was only limited to the topsoil layers. Furthermore, inadequate soil P desorption results in soil active P pool possibly not providing sufficient supplement to labile P pool. The inadequacy of this assumption is not apparent when P input or mineralized soil P is high. However, under a situation in which those P sources are very limited (i.e., the Control and Fertilizer treatments in this study), the soil profile depth for P assimilation by plant roots should be set to be the same as the rooting depth to reduce P depletion in the top layers. However, the total labile P simulated for the entire soil profile was not affected by the error in simulating labile P in the topsoil layers.

3.3. Plant P uptake and crop yield

Simulated P_{upt} matched well with the observed data (Table 9), and the PBIAS and R^2 values were all in the acceptable range (except for the Control treatment). For the calibration dataset, the simulation statistics indicated "very good" agreement for Manure_36TA with PBIAS = -8.84 % and $R^2 = 0.99$, and "good" agreement for Manure_36TB treatment with PBIAS and R^2 of −3.64 % and 0.72, respectively. In contrast, the statistics for Manure_18TA and Manure_18TB were "satisfactory" with PBIAS values of 3.85 % and 23.68 %, respectively, and R^2 values of 0.56 and 0.69, respectively. For the validation dataset, the simulation statistics for the Fertilizer treatment were "good" (PBIAS = 8.36 % and $R^2 = 0.60$). "Satisfactory" performance was indicated for the Manure_52TA and Manure_52TB treatments with |PBIAS| between 15 % and 30 % and $R^2 > 0.40$. The simulation result for the Control treatment was "unsatisfactory" due to an R^2 value of 0.38 as the model overestimated P uptake by barley.

The analysis of crop yield produced similar results (Table 9). RZWQM2-P simulated the crop yield well. For the Control treatment, the simulated results were "good" with PBIAS = 13.93 %. The statistics for all other treatments indicated "very good" agreement (PBIAS within ± 10 % and $R^2 > 0.80$). The average PBIAS for simulated sugar beet yield was −5.70 % using the DSSAT sugar beet model, comparable with the PBIAS obtained by Koehn et al (2021) when using the HERMES sugar beet model. This minor difference, therefore, suggests that both the DSSAT and HERMES models perform similarly in simulating sugar beet yield.

3.4. Long-term impacts of manure applications on soil P recovery

The simulated total P_{lab} for the Continuous treatment (Fig. 2a) increased from an initial value of 131 kg ha^{-1} to 2355 kg ha^{-1} in the soil profile (0–154 cm) after 24 years of manure P applications at a rate of roughly 347 kg ha^{-1} per year. This amount of P application led to about 2.6 times higher in P_{lab} than observed for the recovery treatment (898 kg ha^{-1}) in which the same P rate was applied for the first eight years followed by no P input for the remaining 16 years. For the Continuous treatment, P_{lab} increased over the 24 years at a rate of 92 kg ha^{-1} yr^{-1}. For the recovery treatment, P_{lab} started decreasing at a rate of 10 kg ha^{-1} yr^{-1} after the P input was terminated in year 9 as a result of an annual average P removal rate of 60 kg ha^{-1} yr^{-1} by crop grain or tubers, and assimilated into the soil organic P pools (P^{stab}_{inorg} and P^{stab}_{org}). At the end of

Table 10
Simulated P content changes in separate soil layers from different P pools during a 24-year simulation period, and their balance as simulated by RZWQM2-P for three scenarios.

Soil layer	P_{lab}	P_{act}	P_{inorg}^{stab}	P_{org}^{stab}	P_{org}^{frsh}	Balance of total P pools
cm	kg ha^{-1}					
			Continuous			
0–15	1286.53	331.42	3361.48	−158.58	−14.12	4807
15–30	321.57	39.61	823.66	−77.09	27.63	1135
30–60	144.41	20.18	263.24	−434.24	0.71	−6
60–90	161.53	22.43	323.84	−508.14	−0.02	0
90–122	163.51	16.92	364.32	−544.78	0.00	0
122–154	146.19	6.46	361.10	−513.76	0.00	0
			Recovery			
0–15	−24.94	−40.13	1121.15	−158.58	−14.12	883
15–30	176.47	24.77	566.56	−77.09	27.63	718
30–60	144.40	20.18	263.23	−434.24	0.71	−6
60–90	161.53	22.43	323.84	−508.14	−0.02	0
90–122	163.51	16.92	364.32	−544.78	0.00	0
122–154	146.19	6.46	361.10	−513.76	0.00	0
			Control_LT			
0–15	−30.69	−58.15	−369.80	−14.63	1.90	−471
15–30	−5.65	−12.00	−81.84	45.96	25.55	−28
30–60	−0.23	−0.70	−6.56	−31.76	0.42	−39
60–90	5.84	0.14	11.32	−18.19	−0.02	−1
90–122	6.10	0.10	12.67	−18.89	0.00	0
122–154	1.27	0.02	2.84	−4.14	0.00	0
			Fertilizer_LT			
0–15	−39.60	−72.09	−288.75	11.79	−13.47	−402
15–30	55.99	3.88	232.56	117.24	33.09	443
30–60	−0.39	−0.95	−0.32	−28.55	0.85	−29
60–90	5.70	0.10	11.34	−18.09	−0.02	−1
90–122	6.08	0.13	12.55	−18.79	0.00	0
122–154	1.29	0.08	2.75	−4.12	0.00	0

A positive value means P input and a negative value means P loss; P_{lab} is labile P; P_{act} is active inorganic P; P_{inorg}^{stab} is stable inorganic P; P_{org}^{stab} is stable organic P; P_{org}^{frsh} is fresh organic P; Balance is the summation of all P pool changes.

the long-term simulation (year 24), P_{lab} decreased by 15.68 % from 2001 (year 8) when the application of P was discontinued in the Recovery treatment. The change in P_{lab} mainly occurred in the surface soil layer (0–15 cm). Therefore, the P_{lab} amount in this soil layer for the Continuous treatment reflected a steady accumulation with time (Fig. 2b), from 53 to 1339 kg ha^{-1}. In contrast, P_{lab} for the Recovery treatment (Fig. 2c) increased to 531 kg ha^{-1} in the surface soil layer after eight years of P applications at a rate that was the same as observed for the Continuous treatment, but then declined to 25 kg ha^{-1} because of no further P applications in the following 16 years. This final P_{lab} value was lower than the initial labile P content. The P_{lab} in the surface soil layer took 14 years to return to the initial level. In the deeper soil layers (15–154 cm), the labile P continued to increase over time for both Continuous and Recovery treatments. Since our Recovery treatment was the worst scenario, the P drawdown time would be less than 14 years for other manure treatments based on our model simulation.

The Control_LT scenario (no manure and fertilizer input for the entire 24-year simulation period) showed that the total P_{lab} in the entire soil profile (Fig. 3a) decreased from an initial value of 101 kg ha^{-1} to 77 kg ha^{-1} at the end of year 24, and then stabilized in the range of 70–80 kg ha^{-1}. Fig. 3b depicts the labile P dynamics in each soil layer. In the top three soil layers (0–15, 15–30, and 30–60 cm), labile P oscillated over time, but overall decreased. The changes in the top two soil layers (0–15 and 15–30 cm) were more obvious because the plants took up P from surface soil layers first. In the 60–90 and 90–120 cm soil layers, labile P increased slightly over time. In the deepest soil layer (120–154 cm), labile P remained nearly constant due to no P exchange activities occurring in deep soil layers. Similarly, the total P_{lab} in Fertilizer_LT scenario oscillated (Fig. 3c) in the range of 128 kg ha^{-1} to 230 kg ha^{-1}. The labile P fluctuated mainly in the top two soil layers (Fig. 3d) and gradually changed in a fixed range due to fertilizer P supply, while the labile P in 60–90 cm soil layer showed a downward tendency. Similar to Control_LT, labile P increased slightly in deeper soil layers (90–154 cm). Finally, the soil total P_{lab} recovered to 140 kg ha^{-1} after every crop rotation, which is only 9.37 % higher than initial total P_{lab} content (128 kg ha^{-1}) in Fertilizer_LT treatment. The average annual simulated crop yields for potato, barley, and sugar beet were affected by P stress in the Control_LT treatment, with a decrease of 7.1 %, 13.2 %, and 2.7 %, respectively.

Our simulation results showed that it took a long time for the P_{lab} content in the soil to return to the initial status for those plots being amended with high manure application rates. The main P_{lab} loss for the Recovery treatment was through plant uptake of P, which was 1449 kg ha^{-1} for the 24 simulation years or 47.47 % of the total input P (eight years of manure application, 2552 kg ha^{-1}, and 24 years of residue, 501 kg ha^{-1}). The total P loss through runoff was only 4.05 kg ha^{-1} over 24 years and no P loss occurred through deep seepage at this experimental site, which is negligible compared with the total amount of plant uptake P from soil (1449.41 kg ha^{-1}) and soil total P content (22461 kg ha^{-1}) over 24 years. All P_{lab} losses occurred in the surface soil layers, while labile P increases in the deep soil layers (30–154 cm) were caused by P transfer between different P pools (Table 10). Fig. 3 illustrates that total P_{lab} did not decrease to zero during the 24-year simulation period but fluctuated within a range when no or less P applied. The fluctuating tendency of total P_{lab} was the same as that of P_{lab} in the surface soil. In Control_LT treatment, the degradation of residue and organic matter was thought to be partly responsible for the P_{lab} increase in the soil over time that resulted in part of P_{upt} being returned to the soil and the transfer of P_{lab} from P_{org}^{stab} and P_{org}^{frsh}. While the total P_{lab} decrease was mainly caused by plant uptake of P, desorption and immobilization of P in the soil led to P_{lab} being transferred to P_{act} and P_{org}^{frsh} (Fig. 4).

Although the P_{lab} in the first soil layer decreased to 25 kg ha^{-1} after 16 years of P drawdown phase in Recovery treatment, the final total P_{lab} content was still up to 898 kg ha^{-1} and approximately 6 times higher than the final total P_{lab} content in Fertilizer_LT treatment (146 kg ha^{-1}). The simulation results showed that the total input soil P from residue was 21 kg P ha^{-1} yr^{-1} in the Continuous treatment and 22 kg P ha^{-1} yr^{-1} in Fertilizer_LT treatment, which indicated that high manure application increases soil P accumulation. In the Fertilizer_LT and Control_LT treatments, there was almost no increase in P_{lab} in the soil layer below 120 cm (Fig. 3), while P_{lab} showed an increasing trend in the Continuous treatment. This may have been caused by a higher ratio between P_{inorg}^{stab} and P_{act}, leading to more P_{act} moving to the P_{inorg}^{stab} pool through slow absorption and less P from P_{act} being transferred to P_{lab} pool.

4. Conclusions

The impact of high manure P amendments on P_{tot}, P_{lab}, P_{upt}, and crop yield were simulated using the modified RZWQM2-P model for an irrigated field amended with manure. The simulation results showed that RZWQM2-P performed well in predicting P_{tot} and P_{lab} compared with experimental data, although simulations of P_{lab} were less accurate. The modified model was considered acceptable because it worked well for most of the treatments based on simulation statistics. A long-term simulation indicated that P_{lab} in the surface soil layer was able to recover to the initial level 14 years after manure P applications were terminated. For deeper soil layers (60–154 cm), the supplying of P from other P pools resulted in increasing P_{lab} over time. The main P consumption activities of soil labile P (runoff P loss and plant uptake of P) occurred in the surface soil layers. Therefore, applying the proper amount of P to a farm field will reduce soil leachable P and the risk of P pollution. For the crop rotation evaluated in this study, applications of about 120 kg P ha^{-1} yr^{-1} would be sufficient for crop growth without

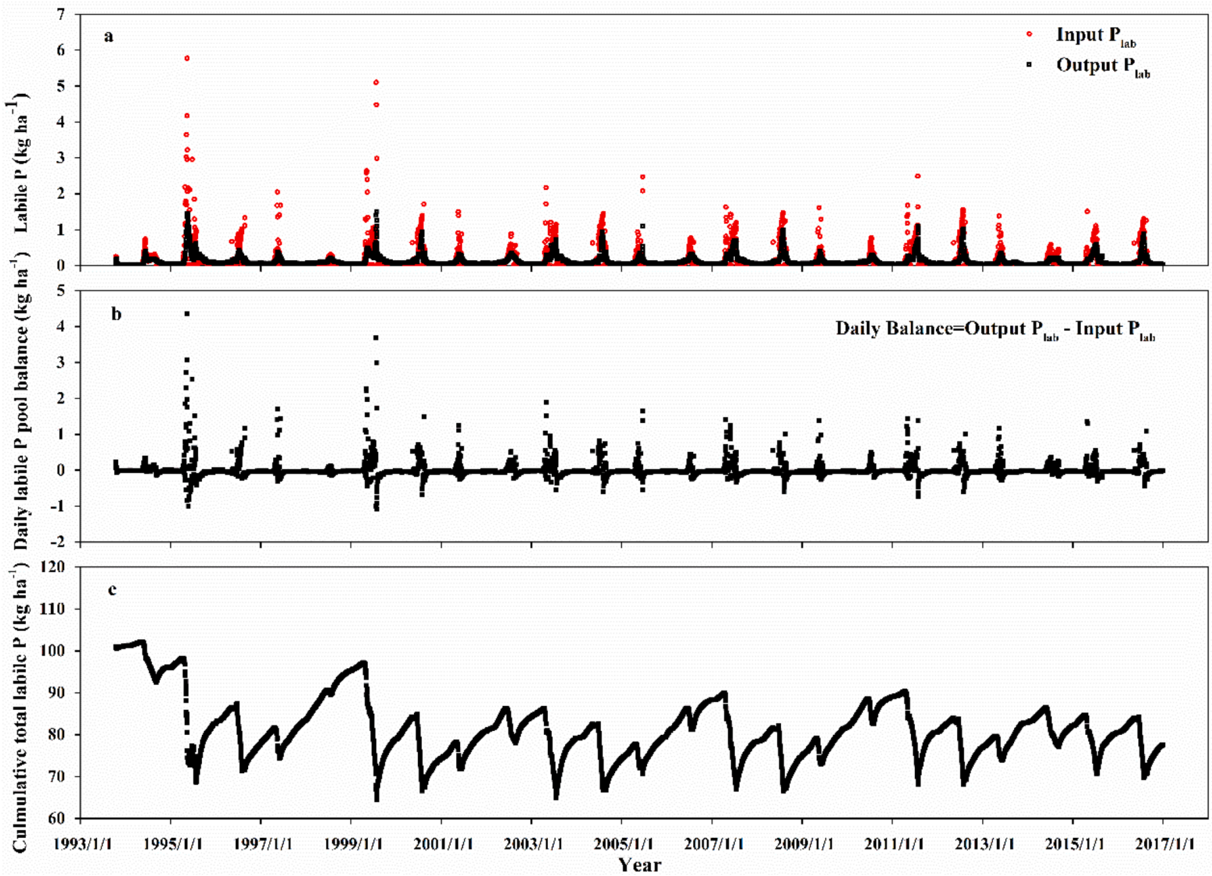

Fig. 4. Long-term simulation results of input and output P in labile P pool (a), daily labile P pool change (b), and cumulative labile P (c) from all soil layers in the Control_LT treatment as simulated by RZWQM2-P.

causing surface soil P accumulation, Manure_18TA treatment meets this criterion in this study. Meanwhile, long-term simulation results of fertilizer treatment suggested that when P application rate at about 40 kg P ha^{-1} yr^{-1}, the soil total labile P presented the lowest risk for P pollution. Among our manure treatments, the P application rate of 18 T biannually is closest to meet this P criterion. In the future, we hope to improve the accuracy and reasonableness of simulations of soil P dynamics in RZWQM2-P by improving the simulation of P activities between adjacent soil layers and by expanding the depths to which P is added by manure applications. The simulation of soil P content by RZWQM2-P needs to be further tested using additional datasets.

CRediT authorship contribution statement

Peng Pan: Conceptualization, Methodology, Writing – original draft. **Zhiming Qi:** Conceptualization, Methodology, Software, Writing – original draft. **Anita Koehn:** Methodology, Resources, Writing – review & editing. **April Leytem:** Formal analysis, Resources, Writing – review & editing. **Dave Bjorneberg:** Resources. **Liwang Ma:** Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Ackowledgment

We would like to appreciate Natural Sciences and Engineering Research Council of Canada (NSERC 2019-05662) for the financial support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compag.2023.107672.

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