Soil & Tillage Research 227 (2023) 105587

Contents lists available at ScienceDirect

Soil & Tillage Research

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

Modeling phosphorus losses to subsurface drainage under tillage and compost management

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ARTICLE INFO

Keywords:
P modeling
RZWQM2-P
Subsurface drainage
P losses
Tillage

ABSTRACT

While agriculture consumes 80–90 % of the world's annual phosphorus (P) production, only 20 % is utilized effectively by plants. Efforts to reduce agricultural P losses through various best management practices (BMPs) including no-till and organic fertilizer have helped substantially mitigate P pollution. The objective of this study is to investigate the long-term P losses through tile drainage as affected by tillage and compost amendment using the newly-developed RZWQM2-P model. We found that the model accurately simulated field-measured annual drainage water flow, as well as annual particulate P (PP) and total P (TP) losses in tile drainage, although it underestimated dissolved reactive P (DRP) when compost was applied. Long-term simulation results showed that tile drainage flow was negatively correlated with tillage intensity (TI, between 0 and 1), and tile-drainage-borne P losses were negatively correlated with TI and manure/compost P mix efficiency (ME, between 0 and 1) with soil after tillage. Specifically, when TI increased from 0 (no-till) to 0.93 (moldboard plow), drainage flow, DRP, and PP losses decreased by 11.49 %, 48.12 %, and 30.29 %, respectively. Similarly, when ME increased from 0 (no-till) to 0.5 (Tandem Disk), DRP and PP losses through drainage flow reduced by 53.98 % and 30.95 %, respectively. ME was not directly associated with drainage flow volume in the model. Overall, the RZWQM2-P model can accurately simulate PP and TP losses on an annual basis, although DRP loss prediction still needs to be improved, and it can be used as a tool to evaluate tillage effects on P loss from tile-drained agricultural land under manure or compost application.

1. Introduction

Essential to crop growth, phosphorus (P) plays a key role in maintaining high crop yields and achieving food security (Cordell et al., 2011) so, not surprisingly, P is supplied as a macro-nutrient in over 90 % of major field crop fertilizers (Rawashdeh and Maxwell, 2011). On a global basis, the agricultural sector leads in the consumption of P, accounting for 80–90 % of the world P demand (Childers et al., 2011). The main source of P used in agriculture is phosphate rock, a non-renewable mineral resource which is expected to be exhausted within 70–140 years (Li et al., 2018). However, of the P applied to cropland as fertilizers, only 20 % was taken up by plants (Li et al., 2019a), the remainder being left in soils and may subsequently enter aquatic ecosystems and pose a threat to water quality and aquatic organisms (Liu and Qiu, 2007). In addition, too much phosphorus accumulated in the soil can be harmful to plant growth and cause zinc and iron deficiency.

To mitigate P pollution in water bodies, two main approaches have emerged: reducing phosphorus loss from contaminated sources and recovering phosphorus from contaminated water bodies. Currently, few phosphorus recovery technologies have been widely implemented as most technologies are not profitable (Li et al., 2019b,c). Developing field management practices to reduce phosphorus losses into waterways is a more practical option, and those practices have been assessed through numerous field experimental studies worldwide for different climate-soil-plant systems. However, these experiments are usually very costly and time-consuming, and usually cannot cover all climate-soil-plant systems or a long-time span. Comparatively, using computer models calibrated and validated with field data obtained over a limited number of years at certain environmental settings, can allow one to evaluate hypothetical treatment effects over a much more extended period, and in a much more economical and timely manner.

Recent interest in employing soil amendments of manure and

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https://doi.org/10.1016/j.still.2022.105587
Received 14 April 2022; Received in revised form 11 November 2022; Accepted 16 November 2022
Available online 2 December 2022

Table 1
Details on tillage and compost application at both experiment farms. Description: This table includes application date of compost and tillage, and the properties of used compost in field experiment.

Year	*Crop*	*Tillage date*		*Compost*							
		disk	Mold-board	Date	Rate	Organic matter	N (g kg^{-1})		P (g kg^{-1})		C: N
					(Mg d.w. ha^{-1})	(g kg^{-1})	Total	NH_4-N	Total	Water extractable	
1998	soybean	10-May	5-Nov	10-Dec	75	196	17.4	0.471	2.96	0.067	6.53
1999	soybean	2-May	15-Oct	21-Oct	75	480	16.0	0.033	2.08	0.082	17.40
2000*	maize	10-May	15-Nov	8-Dec	75	338	16.7	0.25	2.51	0.075	11.97
2001	soybean	2-May	20-Oct	No compost application							

[*] The properties of compost applied in 2000 are not available but it was produced following the same procedure, so the mean value for 1998 and 1999 was used for 2000. d.w.: dry weight. Tillage density was 15 cm for moldboard plow and 10 cm for disking. Crop planting parameters are in Appendix Table A1.

Table 2
Initial soil P concentration and Calibrated soil hydraulic parameters used in model.

Soil layer	Initial Soil P		Calibrated soil hydraulic parameters			
(m)	Labile g kg^{-1}	Total g kg^{-1}	P_b (kPa)	λ (-)	k_{sat} (mm h^{-1})	k_{lat} (mm h^{-1})
0–0.01	0.023	0.90	-20.00	0.22	4.5	2.5
0.01–0.20	0.021	0.90	-21.00	0.20	5.0	5.0
0.20–0.40	0.011	0.65	-21.50	0.20	5.0	5.0
0.40–0.60	0.005	0.50	-21.50	0.20	5.0	5.0
0.60–1.10	0.005	0.40	-16.64	0.20	1.9	1.9
1.10–3.00	0.001	0.10	-16.64	0.19	1.9	1.9
3.00–3.09	0.001	0.10	-16.16	0.19	0.1	0.1

P_b, air entry pressure; λ, pore size index; k_{sat}, saturated hydraulic conductivity; k_{lat}, lateral hydraulic conductivity;.

Table 3
Calibrated parameters for soil, tillage, and phosphorus cycle.

Parameters	Calibrated values
Albedo	
Dry soil	0.5
Wet soil	0.7
Crop at maturity	0.8
Fresh residue	0.22
Tillage	
Moldboard -intensity	1.0
Moldboard -mix efficiency	0.25
Disk-intensity	0.4
Disk-mix efficiency	0.5
Macroporosity (m^3 m^{-3})	0.009
P extraction coefficient	1.0
Soil filtration coefficient	0.1
Soil detachability coefficient	0.4
Soil replenishment coefficient	1.0
Initial DRP in ground water reservoir (kg ha^{-1})	14
Initial PP in ground water reservoir (kg ha^{-1})	13
Plant P parameters	
Maize	
Biomass P Fraction at Emergence	0.002
Biomass P Fraction at 50% Maturity	0.001
Biomass P Fraction at Maturity	0.0008
P uptake distribution parameter	5.0
Soybean	
Biomass P Fraction at Emergence	0.004
Biomass P Fraction at 50 % Maturity	0.002
Biomass P Fraction at Maturity	0.001
P uptake distribution parameter	5.0

compost to improve plant growth and soil quality, as well as promoting resource recycling has met with some environmental worries (Martínez-Blanco et al., 2013). When applying these organic wastes onto agricultural land, it is difficult to match the amounts of P released from organic amendments to crop requirements. Excessive amendment of the soil with organic waste can lead to an increased risk of P loss (Zhang et al., 2017). Few experimental studies have investigated the long-term

Table 4
Statistical model performance evaluation criteria.

Rating	Model accuracy evaluation statistics		
	|PBIAS|	R^2	IoA
Water flow			
Satisfactory	10–15%	0.6–0.7	0.75–0.85
Good	3–10%	0.7–0.75	0.85–0.9
Very Good	< 3%	> 0.75	> 0.9
Phosphorus			
Satisfactory	15–30%	0.4–0.65	0.75–0.85
Good	10–15%	0.65–0.80	0.85–0.9
Very Good	< 10%	> 0.80	> 0.9

Table 5
Tillage practices applied in RZWQM-P long-term simulation. Description: Tillage intensity from RZWQM2 default and mix efficiency was adopted from GLEAM model documentation.

Implement name	Tillage intensity	Mix efficiency	Tillage depth (cm)
No till	0.00	0.00	0
Paraplow	0.20	0.05	15
Chisel plow (Standard treatment)	0.25	0.10	13
Moldboard	0.93	0.30	15
One-way disk	0.40	0.40	10
Tandem disk	0.50	0.50	10

effect of soil amendment with organic waste on P loss, which can be achieved by a well-calibrated computer model.

Moreover, other agricultural management practices (*e.g.*, drainage and tillage) may affect phosphorus loss. For example, tile drainage can increase nutrient loss, by redirecting excess water and nutrients dissolved in the water to the streams (Hanrahan et al., 2020; King et al., 2015; Williams et al., 2015). Historically, tillage practices employed in field experiments have focused mainly on conventional tillage and no-till (Randall and Iragavarapu, 1995; Zhang et al., 2017; Zhao et al., 2001). Given the difficulty and cost of undertaking field experiments, few studies are designed to investigate tillage intensity effects on nutrient loss under compost application.

Agricultural systems models have been widely used to access management practices on crop production and environmental quality. Currently, there are two models, RZWQM2-P (Root Zone Water Quality Model 2-Phosphorus, Sadhukhan et al., 2019a) and DRAINMOD-P (Askar et al., 2021), capable of simulating P losses from tile-drained field. Compared to DRAIMOD-P, RZWQM2-P model is featured with detailed tillage and organic fertilizer subroutines which provide 29 tillage methods and 15 types of manure, respectively, in the database. The model was tested using P loss data collected from a tile-drained Canadian cropland amended with manure P (Sadhukhan et al., 2019b). As a one-dimensional (vertical soil profile) field-scale model,

Table 6
Model performance on simulating drainage flow and P losses and simulated P balance. Description: In P balance, manure P, fertilizer P and residue P are added P; while plant uptake P, DRP and PP losses are lost P from field.

Statistics	Calibration		Validation	
	$CT\text{-}CMP_{75}$	$NT\text{-}CMP_{75}$	$CT\text{-}CMP_0$	$NT\text{-}CMP_0$
	Drainage (mm)			
Obs. mean	112.37	99.02	75.84	104.51
Sim. mean	102.71	107.07	86.21	96.49
Rating	good	good	satisfactory	good
	DRP (g ha^{-1})			
Obs. mean	181.62	361.83	45.89	57.38
Sim. mean	219.95	262.42	164.57	195.59
Rating	satisfactory	satisfactory	unsatisfactory	unsatisfactory
	PP (g ha^{-1})			
Obs. mean	347.11	323.32	274.1	361.73
Sim. mean	277.43	338.79	209.29	253.45
Rating	satisfactory	good	satisfactory	unsatisfactory
	TP (g ha^{-1})			
Obs. mean	555.32	760.92	331.38	433.60
Sim. mean	570.70	688.68	428.72	514.24
Rating	very good	good	satisfactory	unsatisfactory
P Components	**P balance (kg ha^{-1})**			
Manure P	567	567	0	0
Fertilizer P	54	54	54	54
Residue P	23.11	22.30	23.09	22.38
Plant uptake P	51.30	47.41	51.30	47.36
DRP loss				
Runoff	21.60	43.76	1.95	3.95
Drainage	0.84	1.02	0.62	0.78
PP loss				
Runoff	3.17	5.82	0.97	1.93
Drainage	1.00	1.24	0.75	0.98

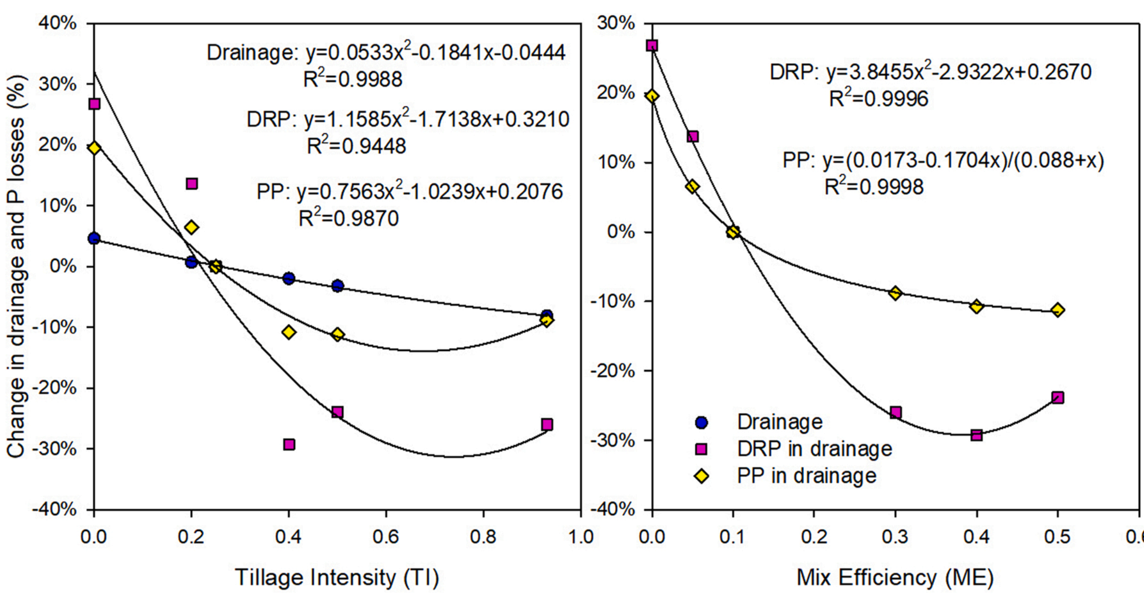

Fig. 1. Impact of a) tillage intensity (TI) on tile drainage, DRP and PP losses, and b) tillage mix efficiency (ME) on DRP and PP losses through drainage. Description: DRP means dissolved reactive P and PP means particulate P. This figure illustrates the change tendency of drainage volume, DRP&PP losses through drainage as TI&ME increase respectively, the standard treatment is TI= 0.25&ME= 0.1.

the RZWQM2 model integrates physical, chemical, and biological process models to simulate water, nutrient, and pesticide dynamics within the crop root zone, as well as crop growth (Ahuja et al., 2000; Malone et al., 2004a). The RZWQM2 model has been used to study the effects of management practices on hydrology, chemical losses to tile drains, crop growth, energy balance and CO_2 emission in several countries (Jiang et al., 2018; Liu et al., 2017; Ma et al., 2007a; Qi et al., 2012), in particular under various tillage (Ahuja et al., 1998; Ding et al., 2020; Gillette et al., 2017; Karlen et al., 1998; Kozak et al., 2007; Kumar et al., 1999; Ma et al., 2007b; Malone et al., 2003, 2014) and manure (Bakhsh et al., 1999; Geisseler et al., 2012; Kumar et al., 1998; Ma et al., 1998) management practices. The newly developed P module in RZWQM2-P (Sadhukhan et al., 2019a) simulates P dynamics following the application of inorganic (Sadhukhan et al., 2019a) or organic fertilizer (Sadhukhan et al., 2019b). Specifically, it tracks the fates of dissolved reactive P (DRP) and particulate P (PP) lost through subsurface drainage and surface runoff. However, the newly developed RZWQM2-P model was never tested against observed drainage P loss data under contrasting tillage management practices. Meanwhile, the long-term effects of conservation tillage practices on mitigating P pollution are unknown.

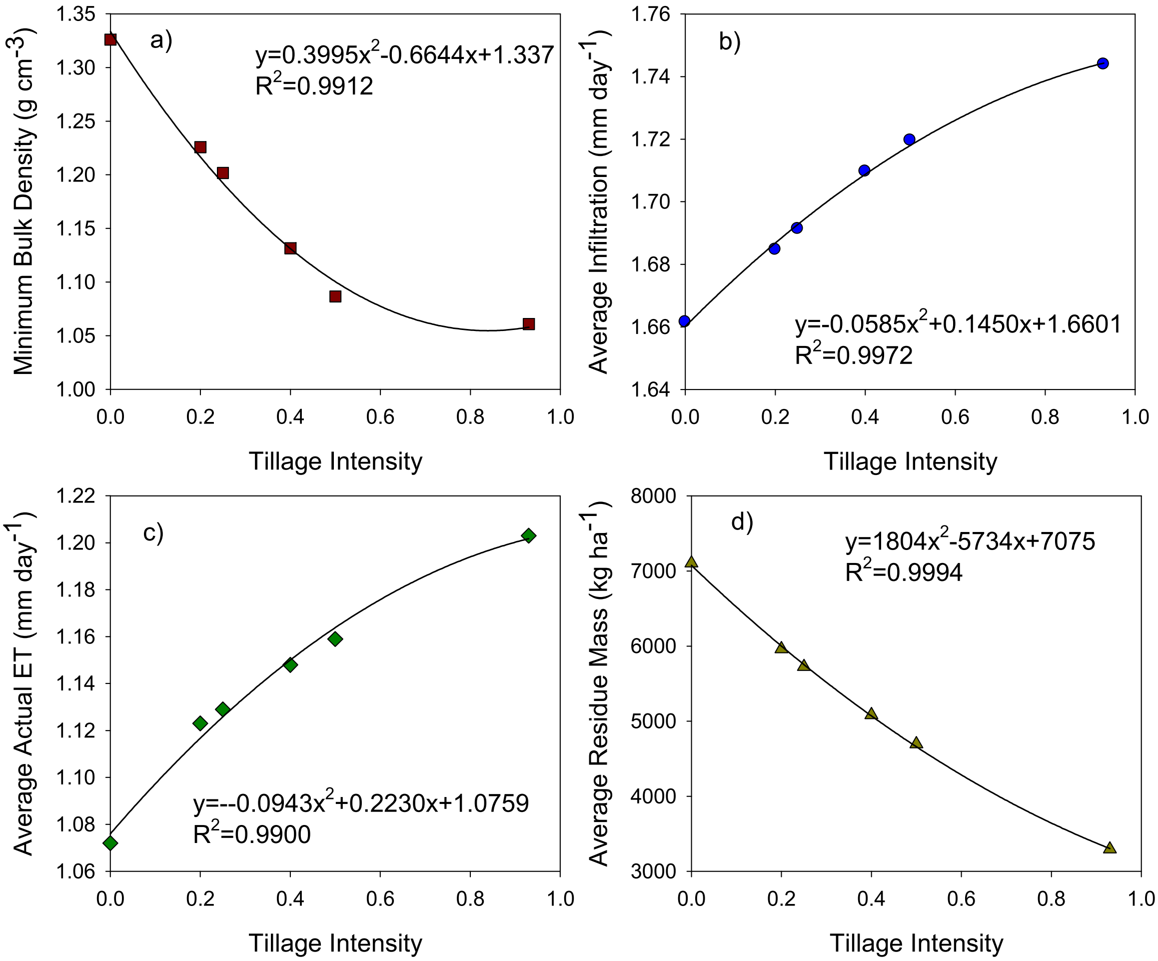

Fig. 2. Simulated effects of tillage intensity on (a) soil bulk density, (b) infiltration, (c) soil evaporation, d) soil surface residue cover change after tillage. Description: This figure illustrates the change tendencies of a) the minimum soil bulk density in soil tillage depth (15 cm), b)&c) average daily water infiltration and actual evapotranspiration and d) average annual surface residue mass as tillage intensity increases.

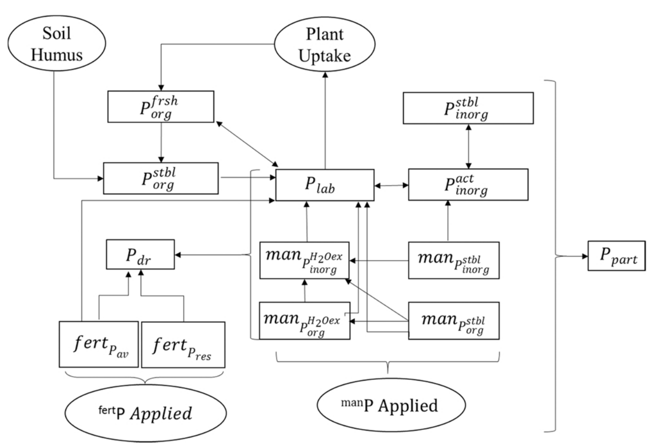

Fig. A1. RZWQM2-P Model's P pools.

Therefore, the objectives of this study are: 1) to assess the performance of the RZWQM2-P model in simulating tile drainage flow, DRP and PP losses from tile-drained plots under contrasting tillage and compost management practices, and 2) to quantify the long-term effects of tillage intensity (TI) and tillage mix efficiency (ME) on P losses through tile flow using the model.

2. Materials and methods

2.1. Field experiment

The observed P data to assess the performance of RZWQM2-P model came from a field experiment conducted on two neighboring farm fields situated near South Woodslee in southern Ontario, Canada during September 15, 1998 – November 14, 2001 (Zhang et al., 2017). The same four-year rotation of maize in 2000 and soybean in 1998, 1999 and 2001 was implemented at both sites. Farm A (lat. 42° 12′ 15″ N, long. 82° 44′ 50″W) had been under no-till management since 1989, whereas Farm B (lat. 42° 12′ 15″ N, long. 82° 45′ 58″ W) had been under conventional tillage, namely moldboard plowed after harvest and disked prior to next spring's planting date, from 1991 onward. Each farm site was then divided into two plots, with each plot size at 2–2.4 ha. The soil was a Brookston clay loam (Orthic Humic Gleysol; Evans and Cameron, 1983) at both sites. Weather data (air temperature, precipitation, relative humidity, solar radiation and wind speed) was collected for the period of January 01, 1991 to December 31, 2001 from the Woodslee weather station, located 1.5 km from both study farm fields.

The treatments at both sites included a factorial combination of two contrasting compost treatments, 0 or 75 Mg dry weight (d.w.) ha^{-1} (CMP_0 or CMP_{75}) and two contrasting tillage practices, no till and conventional tillage (NT and CT), resulting in four treatment combinations $NTCMP_0$, $NTCMP_{75}$, $CTCMP_0$, $CTCMP_{75}$. Under both tillage practices, commercial fertilizers at the rates recommended locally (200 kg N ha^{-1} and around 17 kg P ha^{-1}) were surface-applied on 30

Table A1
Planting parameters for two experimental fields, one under no-till management (Field A) and the other under conventional tillage (Field B), situated on a farm near South Woodslee, ON.

Year	Crop	Planting parameters						
		Farm A (no-till)			Farm B (conventional tillage)			
		Date (d. mo.)	Density (seed m^{-2})	Interrow spacing (m)	Date (d. mo.)	Density (seed m^{-2})	Interrow spacing (m)	Harvest date for both farms
1999	soybean	12 May	57.9	0.38	07 May	56.7	0.38	23 September
2000	maize	07 June	7.2	0.76	07 May	7.2	0.76	23 September
2001	soybean	12 May	57.9	0.38	04 May	55.5	0.38	23 September

Table A2
The correspondence between year and period of observed data.

Year	Collection Period	
	Start Date	End Date
1998	9/15/1998	2/3/1999
1999	2/3/1999	3/8/1999
	3/8/1999	4/1/1999
	4/1/1999	4/14/1999
	4/14/1999	4/20/1999
	4/20/1999	4/27/1999
	4/27/1999	8/6/1999
	8/6/1999	4/25/2000
2000	4/25/2000	5/23/2000
	5/23/2000	6/26/2000
	6/26/2000	7/31/2000
	7/31/2000	8/9/2000
	8/9/2000	9/25/2000
	9/25/2000	10/12/2000
	10/12/2000	11/14/2000
	11/14/2000	12/20/2000
	12/20/2000	2/1/2001
2001	2/1/2001	2/14/2001
	2/14/2001	3/19/2001
	3/19/2001	4/4/2001
	4/4/2001	4/18/2001
	4/18/2001	5/15/2001
	5/15/2001	5/30/2001
	5/30/2001	8/21/2001
	8/21/2001	10/16/2001
	10/16/2001	11/14/2001

Table A3
Statistic results when evaluating the RZWQM2-P model performance against periodical data.

IoA				
	$CT\text{-}CMP_{75}$	$NT\text{-}CMP_{75}$	$CT\text{-}CMP_0$	$NT\text{-}CMP_0$
Tile drainage	0.41	0.36	0.54	0.34
DRP loss	0.24	0.18	0.19	0.21
PP loss	0.59	0.47	0.77	0.49
R^2				
	$CT\text{-}CMP_{75}$	$NT\text{-}CMP_{75}$	$CT\text{-}CMP_0$	$NT\text{-}CMP_0$
Tile drainage	0.00	0.00	0.04	0.01
DRP loss	0.07	0.02	0.02	0.01
PP loss	0.04	0.00	0.38	0.08

April each year.

The compost of tree leaves and other yard wastes was processed in a turned open-air windrow system (Essex-Windsor Solid Authority, ON, Canada) with a final objective C/N ratio approximately 15.5. While the properties of the compost produced in 2000 are not available, the mean value for 1998 and 1999 was applied for 2000, as the compost was prepared following the same procedure using materials from the same source. The application rate and properties of the compost are listed in Information associated with compost and tillage are summarized in Table 1.

Each plot contained five subsurface tile drains spaced 8.7 m apart at an average depth of 0.6 m. The drainage water from each plot was discharged into an individual manhole located in a monitoring shed equipped with a calibrated tipping bucket system to measure drainage flow on a year-round continuous basis from September 1998 through November 2001 and aggregated on an annual basis. This allowed for the collection of tile drainage samples on a flow-weighted basis using the ISCO model 2900 (Lincoln, Nebraska, USA) automatic samplers which were programmed to collect one sample for every 10,000 L in the CT field and 25,000 L in the NT field. A maximum of 24 consecutive samples were collected over a period of time and were mixed to create a composite sample for P analysis (Tan et al., 2002; Zhang et al., 2017). Prior to analysis in the laboratory, water samples were filtered through a 0.45-µm filter and phosphorus (P) was measured using the colorimetric analysis procedure for dissolved reactive P (DRP) (USEPA, 1983). The total dissolved P (TDP) of filtered water samples were analyzed using the acidified ammonium persulfate oxidation procedure (USEPA, 1983). The concentrated sulfuric hydrogen peroxide digestion method (Thomas et al., 1967) was used to analyze Total P (TP) in unfiltered water samples. Particulate P (PP) was computed as the difference between TP and TDP. (Table A1).

2.2. Model Description and Modification

In the RZWQM2, the soil water retention is described by the Brook-Corey equation (Brooks and Corey, 1964). The Green-Ampt equation (Green and Ampt, 1911) is adopted for infiltration when rainfall or irrigation occurs, and the Richards equation (Richards, 1931) is used for soil water redistribution after rainfall or irrigation events. RZWQM2 contains a tile drainage component based on the Hooghoudt's steady-state equation (Herman and Jan van, 1963). The model simulates macropore flow using Poiseuille's law. The crop growth subroutine is adapted from DSSAT 4.0 crop models (Jones et al., 2003).

A variety of real-world options for the timing and methodology of each management practice, such as planting, harvest, tillage, fertilizer/manure/pesticide application, drainage and irrigation, and residue management, are included in RZWQM2. The effects of 29 tillage methods, primary tillage using plows and secondary tillage using cultivators and planters, on soil structure and soil-residue/manure mixture are simulated through user-adjustable parameters such as tillage depth and tillage intensity. In terms of modeling manure effects on crop production and the environment, the schedule timing can be set on a specific date or an offset date from the first day of the crop stages: planting, emergence, and harvest (stage after harvest is defined as layby). The model has a database of 14 different manure types (i.e. beef, dairy, swine) and one user-defined bedding, litter or food processor waste (i.e., compost) with 4 options of application methods (surface broadcast, injected etc.). Users can define the C:N ratio, organic/waste dry matter, and nutrient concentration in the manure/litter. The mineralization of nutrients and their fate and transport are simulated using various organic and inorganic nutrient pools. Details of simulating management practices and CN cycle can be seen in Ahuja et al. (2000).

A phosphorus component was newly developed and incorporated into the RZWQM2 model to establish the RZWQM2-P which is the first available tool to simulate both dissolved and particulate P losses through

Table A4
Simulated and observed tile drainage flow (mm) and model accuracy statistics.

Year	Calibration				Validation			
	CT-CMP75		NT-CMP75		CT-CMP0		NT-CMP0	
	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
1998	52.30	0.00	25.83	0.00	19.84	0.00	10.40	0
1999	80.02	102.69	110.78	106.85	60.66	72.99	99.96	93.14
2000	175.11	154.80	127.53	168.67	125.66	135.38	148.86	160.13
2001	142.03	153.34	131.94	152.75	97.20	136.45	158.83	132.70
Mean	112.37	102.71	99.02	107.07	75.84	86.21	104.51	96.49
PBIAS		-8.60%		8.12%		13.67%		-7.67%
IoA		0.92		0.94		0.94		0.98
R2		0.80		0.96		0.92		0.95

Table A5
Average water balance (mm day^{-1}) simulated by the RZWQM2.

Treatment	Rainfall	Infiltration	ET	Runoff	Drainage	Deep seepage
CT-CMP75	2.21	1.71	1.16	0.49	0.36	0.04
NT-CMP75	2.21	1.65	1.11	0.55	0.37	0.02
CT-CMP0	2.21	1.79	1.29	0.41	0.30	0.04
NT-CMP0	2.21	1.72	1.21	0.48	0.33	0.02

tile drainage under organic and inorganic P amendment, with details found in Sadhukhan et al. (2019a). The structure and dynamics of P pools (Fig. A1) are adopted from the EPIC model (Jones et al., 1984) and the decomposition processes of organic P in manure are from the SurPhos model by Vadas (2014). In general, five P pools, stable inorganic, active inorganic, labile, fresh organic, and stable organic P, are created in the RZWQM2-P model to host all forms of P in soil. P in manure, when applied to the field, is partitioned into water extractable, stable inorganic, and organic P pools. Tillage practices incorporate a fraction of surface manure P into the soil, where the manure water extractable P incorporates into soil labile P pool whereas the manure stable P incorporates into the active P pool of the first soil layer.

However, in the 2019 version of RZWQM-P, the percentage of P transferred from manure/compost pool to soil was simply calculated by subtracting 1.0 from TI (tillage intensity), which is not valid for most cases. Therefore, we modified the model to make ME (P mix efficiency by tillage) an adjustable input parameter with initial values from the GLEAMS model technical report (Knisel et al., 1993), rather than being calculated from TI, to quantify the percentage of P transferred from surface manure inorganic P pools to soil P pools due to tillage. The specific ME values corresponding to different tillage practices can be found from GLEAMS user manual Part 4 "Plant nutrient parameters" (Knisel et al., 1993), while TI values can be found from the RZWQM2 technical report (Table 8.2 in Ahuja et al., 2000). The modified equations for the transfer of P from surface inorganic P pools to soil labile and active inorganic P pools are shown as follows:

$$LabP_a = LabP_b + (Avfertp + Resfertp + Manwip) * T_{mixeffi} \tag{1}$$

$$ActP_a = ActP_b + Mansip * T_{mixeffi} \tag{2}$$

Where,

$LabP_a$=Labile P of the soil layer after the incorporation due to tillage (kg)
$LabP_b$=Labile P of the soil layer before the incorporation due to tillage (kg)

Table A6
Simulated and observed DRP loss through tile drainage (g ha^{-1}) and model accuracy statistics.

Year	Calibration				Validation			
	CT-CMP75		NT-CMP75		CT-CMP0		NT-CMP0	
	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
1998	101.86	0.00	134.51	0.00	11.71	0.00	13.92	0.00
1999	76.77	198.12	142.57	225.64	28.59	137.52	8.08	192.96
2000	295.97	327.72	412.85	389.50	103.54	261.03	37.25	340.79
2001	251.89	353.97	757.40	434.55	39.70	259.72	170.28	248.57
Average	181.62	219.95	361.83	262.42	45.89	164.57	57.38	195.58
PBIAS		21.10 %		-27.47 %		258.63 %		240.84 %
IoA		0.83		0.81		0.40		0.42
R^2		0.62		0.67		0.55		0.13

Table A7
Simulated and observed PP loss through tile drainage (g ha^{-1}) and model accuracy statistics.

Year	Calibration				Validation			
	CT-CMP75		NT-CMP75		CT-CMP0		NT-CMP0	
	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
1999	8.61	29.05	3.27	33.41	17.90	0.00	15.47	17.40
2000	340.27	391.41	298.12	478.29	362.09	314.18	351.58	427.86
2001	692.44	411.81	668.57	504.66	442.30	313.70	718.14	315.10
Average	347.11	277.43	323.32	338.79	274.10	209.29	361.73	253.45
PBIAS		-20.07 %		4.78 %		-23.64 %		-29.93 %
IoA		0.86		0.91		0.94		0.74
R2		0.78		0.74		0.97		0.47

Table A8
Simulated and observed TP loss through tile drainage (g ha-1) and model accuracy statistics.

Year	Calibration				Validation			
	$CT-CMP_{75}$		$NT-CMP_{75}$		$CT-CMP_0$		$NT-CMP_0$	
	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
1999	85.38	227.17	145.83	259.04	46.50	137.52	23.56	210.36
2000	636.25	719.13	710.96	867.79	465.63	575.21	388.83	768.65
2001	944.32	765.78	1425.97	939.21	482.01	573.42	888.42	563.67
Average	555.32	570.70	760.92	688.68	331.38	428.72	433.60	514.23
PBIAS		2.77 %		-9.49 %		29.37 %		18.59 %
IoA		0.94		0.86		0.95		0.68
R2		0.92		0.77		1.00		0.31

$ActP_a$=Active inorganic P of the soil layer after the incorporation due to tillage (kg)
$ActP_b$=Active inorganic P of the soil layer before the incorporation due to tillage (kg)
$T_{mixeffi}$=Tillage mix efficiency (ME, fraction)
Avfertp=Available inorganic fertilizer P pool (kg)
Resfertp=Residual fertilizer P pool (kg)
Manwip=Manure water extractable inorganic P pool (kg)
Mansip=Manure stable inorganic P pool (kg)

2.3. Model initialization, calibration and validation

Data recorded for the management practices at two farm field sites, such as crop species, planting and harvest timing, compost application timing, method, and P rate, tillage timing and method, along with the observed weather data, are used to initialize the model. As initial P concentration in soil were not measured, P concentration in all soil P pools in seven soil layers of an adjacent field within 1 km distance, as listed in Sadhukhan et al. (2019a), was used to initialize the soil P in the model for this study. Concentration of P in labile and total P pools are listed in Table 2. Parameters of the RZWQM2-P model were calibrated using three years of data (Sep 1998-Nov 2001) from the research site, to find suitable values for soil hydraulic parameters and crop parameters that affect phosphorus dynamics in soil under different compost amendment and tillage conditions. The $CT-CMP_{75}$ treatment was used to calibrate the model since it covered both management practices (tillage and compost application), while data fromş $CT-CMP_0$, $NT-CMP_0$, and$NT-CMP_{75}$ were used for validation.

Following the hydrological calibration methods of Ma et al. (2012) and the P losses calibration methods of Sadhukhan et al. (2019a), the value of one parameter was varied at a time within a reasonable range based on the literature. Parameters related to soil hydraulic properties were first calibrated against observed hydrologic data and later parameters directly associated with P activities were calibrated against observed P loss and P uptake data. Nevertheless, in the second stage hydraulic parameters were slightly re-calibrated to improve simulation in P losses without sacrificing the hydrologic simulation. Soil hydraulic parameters [e.g., saturated hydraulic conductivity, k_{sat}; air entry pressure, P_b; lateral hydraulic conductivity, k_{lat}, and macroporosity] were first manually adjusted to fit tile drainage flow. Soil albedo values were adjusted to maintain a reasonable level of evapotranspiration. Subsequently, the DRP loss through tile drainage flow was used to further fine-tune macroporosity, air entry pressure (P_b) and the pore size distribution index (λ) of all soil layers (Table 2 and Table 3).

The modified tillage component of the RZWQM2-P model was calibrated using soil P loss data. The tillage effective depth was set using model default values, 10 cm for disk and 15 cm for moldboard plow. As cracks presented every year in the fields, the macroporosity was adjusted to meet the level of PP lost in drainage flow. The manure and soil P parameters were adjusted to achieve a better simulation on DRP and PP loss through tile drainage. Parameters associated with plant P uptake were calibrated based on the observed crop P uptake in neighboring site (Sadhukhan et al., 2019a) and the observed P losses in this study. Values of the aforementioned parameters are listed in Table 3.

Three model accuracy evaluation statistics were employed, percent bias (PBIAS), Index of Agreement (IoA) and coefficient of determination (R^2) between observed and simulated values, to evaluate the model's performance (Moriasi et al., 2015). PBIAS reflects whether the simulation results are greater or lesser than the observed data (Gupta Hoshin et al., 1999), IoA is a standardized measure of the degree of model prediction error (Willmott, 1981), while R^2 describes the degree of collinearity between simulated and measured data (Moriasi et al., 2007). The rating criteria should vary according to the study objective and uncertainty in measured data (Moriasi et al., 2007; Ma et al., 2011). For example, |PBIAS| of 100% can be acceptable for pesticide simulation because of large experiment errors (Malone et al., 2004b). Table 4 presented the accuracy statistics criteria used in this case. Given the fact that PBIAS for field scale simulation and IoA for annual data are not defined in Moriasi et al. (2015), the evaluation criteria of watershed scale modeling were adopted to evaluate model performance on field scale modeling of this study.

The original observed drainage flow and P loss data were sorted by periods (collection period in Table A2) as only one composite sample was analyzed for DRP and TP in every sorted period. However, the model cannot provide a good simulation result to match the observed data within a short time resolution (Table A3). Possibly, this poor fitting result was caused by the fact that simulated winter drainage was delayed compared to observed data. The observed drainage in February was usually significantly underestimated while overestimated in March and April. Therefore, the periods roughly fell in a year was grouped to an annual value for comparison. Sampling periods and year delineation are shown in Appendix Table A2.

2.4. Model application

The calibrated and validated RZWQM2-P model (CMP_{75} treatments) was then used to simulate the long-term effects of different tillage methods, represented by the tillage intensity (TI) and the manure/compost mix efficiency (ME) due to tillage (Table 5), on P losses in tile drainage in Ontario under the amendment with the same leaf compost and commercial fertilizer application rates as in CMP_{75} treatments. The model drew upon historical weather on the same station (Woodslee weather station) from 1992 to 2018. The same management practices, including crop planting, chemical fertilizer and compost application and schedules, from the calibrated scenario were repeated in this long-term (1992–2018) simulation. Tillage effective depths were set at default values (Table 5). TI & ME = 0 represents no-till treatment. Tillage methods after harvest were changed accordingly. The chisel plow was set as the standard treatment and the simulated results from other tillage methods were compared to values from the chisel plow (TI = 0.25 and ME=0.10) simulation, similar to the comparison conducted by Wang et al. (2022) using the EPIC model. The long-term scenario was subsequently employed to investigate how tillage practices affect P losses through subsurface drainage.

3. Results and discussion

3.1. Annual hydrology

On an annual basis, the statistic results showed that model performance on simulating tile drainage was satisfactory (Table 6) and simulated tile drainage volume matched well with the observed drainage for all treatments (Table A4). For the calibration treatment $CTCMP_{75}$, tile drainage was well simulated with PBIAS of − 8.60 %, IoA of 0.92, and R^2 of 0.80. For all the validation treatments ($NTCMP_{75}$, $CTCMP_0$, and $NTCMP_0$), simulated tile drainage showed high IoA values ≥ 0.92. The model performance for $NTCMP_{75}$ and $NTCMP_0$ are ranked as "good" with |PBIAS| < 10 % and $R^2 \geq 0.95$, and "satisfactory" for $CTCMP_0$ with PBIAS values > 10 %.

The simulated mean annual water balance is presented in Appendix Table A5. Approximately, simulated tile drainage as a percent of mean precipitation compared with simulated runoff was 15.38 % versus 21.83 %. Simulated evapotranspiration represented about 53 % of mean precipitation with an average value of 1.19 mm per day. Predicted deep seepage averaged 0.03 mm, which accounted for about 1 % of mean precipitation. (Table A5).

3.2. Annual drainage phosphorus losses

Simulated and observed annual DRP loss through tile drainage for calibration and validation treatments and associated model accuracy statistics (Table A6), show the simulation result of DRP loss through tile drainage to be satisfactory in the calibration phase (CT-CMP_{75}). The simulated average annual DRP loss averaging to be 219.95 g ha^{-1} over four years versus the observed value of 181.62 g ha^{-1} (PBIAS = 21.10 %, IoA = 0.83, and R^2 = 0.62). For the validation treatments, the simulation results for $NTCMP_{75}$ was "satisfactory" (PBIAS within ± 30 %, IoA > 0.80 and R^2 > 0. 65). However, the simulated results for the validation treatments with no compost ($NTCMP_0$ and $CTCMP_0$) were unacceptable with PBIAS values greater than 200 %. The notable DRP overestimation for the validation treatments of no compost suggests that in the calibration those P parameters may greatly overestimate the DRP release from the soil matrix while underestimating DRP contribution from the compost. Because most adjustable parameters are related to P mineralization from soil matrix while those P parameters for manure or compost decomposition are hard-coded, following the SurPhos strategy. In the next model version update, it is worth trying to set manure decomposition rates adjustable. The overestimation of DRP may be also caused by the initial soil P was adopted from a site nearby rather than measuring labile and total P in soils from this site.

Simulated PP loss in general matched well with the observed data (Table A7). For the calibration treatment $CTCMP_{75}$ the simulated annual PP loss was 277.43 g ha^{-1}, − 20.07 % lower than the observed average value of 347.11 g ha^{-1}. The model accuracy statistics (IoA = 0.86 and R^2 = 0.78) showed a "satisfactory" agreement. For validation treatments, the model accuracy for $NTCMP_{75}$ was "good", (PBIAS within ± 5 %, IoA > 0.90 and R^2 > 0.70) and for $CTCMP_0$ was "satisfactory" (PBIAS within ± 30 %, IoA > 0.90 and R^2 > 0. 95), while the accuracy was unacceptable for $NTCMP_0$ with IoA = 0.74 but very close to the threshold value of 0.75. Similarly, the statistics of TP loss through tile drainage presented a good simulation (Table A8). The calibration result showed a "very good" agreement in simulating TP with PBIAS of 2.77 %, IoA of 0.94 and R^2 of 0.92. The simulation performance for validation treatments, $NTCMP_{75}$ and $CTCMP_0$, were deemed to be "good" and "satisfactory", respectively. However, the TP loss result of $NTCMP_0$ was not satisfactory with the IoA < 0.75 and R^2 < 0.40, which may be affected by the over-prediction of DRP loss for this treatment.

P balance simulated by the RZWQM2-P model for each treatment is also included at the bottom part of Table 6. From the simulation result, no-till practices enhanced the DRP loss through both runoff and drainage compared to conventional tillage, model application results in this case also verified that tillage practice decreased DRP and PP losses compared to no till. Under CMP_{75}, CT practice caused 50.04 % decrease on the overall P loss through runoff than did the NT practice, and 18.58 % fall on overall P loss through tile drainage.

3.3. Long-term impacts of tillage on P loss

As illustrated in Fig. 1a, long-term simulation suggests that TI was negatively correlated to tile drainage volume. Overall drainage flow experienced a 11.49 % reduction when TI increased from 0 (no-till) to 0.93 (moldboard plow). The greater the TI, the lower the simulated bulk density in the tilled zone, indicating higher soil porosity and water infiltration rate (Fig. 2a and b). Meanwhile, tillage increases soil saturated hydraulic conductivity and resulted in higher soil evapotranspiration (Fig. 2c), which is also reported in Schwartz et al. (2010). Evidently, in this study the increased evapotranspiration exceeded the increased infiltration due to tillage.

The long-term simulation suggests that both ME and TI had a greater impact on DRP loss than PP loss. The simulated P losses significantly decreased as TI and ME increased (Fig. 1a & 1b). For example, when TI increased from 0 (no-till) to 0.93 (moldboard plow), DRP, and PP losses decreased by 48.12 %, and 30.29 %, respectively; when ME increased from 0 (no-till) to 0.5 (Tandem Disk), DRP and PP losses through drainage flow were reduced by 53.98 % and 30.95 %, respectively. Our simulated reduction in P loss as affected by tillage is supported by findings from literatures. Some studies suggest that macropores are likely the essential flow pathway for transporting P to subsurface drainage (Klaus et al., 2013; Williams et al., 2016). In the RZWQM2-P model, DRP and PP losses in tile drainage are simulated as a linear groundwater reservoir approach (Steenhuis et al., 1997), where the DRP reaches the groundwater reservoir through matrix flow and macropore flow, while the PP only moves through macropore flow (Sadhukhan et al., 2019a). Many studies support the conclusion that tillage can mitigate the P loss through a reduction in drainage flow and the destruction of soil macropores by tillage (Christianson et al., 2016; Djodjic et al., 2002; Gaynor and Findlay, 1995; Zhang et al., 2017). In a field experiment conducted by Gaynor and Findlay et al. (1995), also on a Brookston clay loam soil, the DRP loss in tile drainage under conservation tillage was 25% greater than that under conventional tillage.

As in RZWQM2-P model ME is only associated with phosphorus transfer among manure P pools, it does not affect drainage flow. Employing the same tillage methods and comparison strategy (using chisel plow as the baseline standard treatment), our study resulted in a similar trend in Wang et al. (2022) in DRP loss under different ME values using the EPIC model, in which strong negative relations were found between ME and DRP loss in tile drainage.

4. Conclusions

The impacts of tillage practices and compost application on tile drainage and DRP, PP and TP loss through tile drainage were simulated with the newly developed RZWQM2-P model for a subsurface-drained experimental field in Ontario. The simulation results indicated that the RZWQM2-P model performed well in simulating annual PP and TP loss through tile drainage compared with observed data. However, the model performance on simulating DRP loss through tile drainage was unsatisfactory for the no compost plots as it may overestimated DRP loss from soil matrix. When evaluating the model against high time resolution data, the performance was not satisfactory due to the shift of simulated winter drainage. The model application showed that tillage could reduce tile drainage and P loss in tile drainage compared with no-till management. The TI was negatively correlated to tile drainage due to higher evaporation. The DRP and PP losses in tile drainage were negatively associated with changes in ME and TI. This study demonstrated that the newly developed RZWQM2-P model could accurately simulate most P dynamics under different compost and tillage conditions, and provided an understanding of the possible long-term impacts of tillage practice on P loss. In the future, we hope to improve the DRP loss simulation by adjusting the manure P mineralization parameters and winter drainage. Meanwhile, as the tile flow and P loss data used in this study is on an annual basis, the tillage effect on P losses as simulated by RZWQM2-P model needs to be further investigated using daily or monthly datasets.

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.

Acknowledgment

This research is sponsored by Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant (2019–05662)-Effect of management practices on hydrology and nutrient losses from a tile-drained field under freeze-thaw conditions. We would like to thank anonymous reviewers for their comments and suggestions.

Appendix A

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