# MODIFICATION OF RZWQM2-P MODEL TO SIMULATE SUBSURFACE PHOSPHORUS LOSS AND SOIL PHOSPHORUS DYNAMICS IN ORGANIC WASTE AMENDED CROPLANDS

BY

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# ABSTRACT

While agriculture consumes 80-90% of the world's annual phosphorus (P) production, only 20% is utilized effectively by plants, the remaining is lost to the aquatic environment or accumulate in the soil. The RZWQM2-P model was newly developed and then incorporated into the RZWQM2 model working as a single tool to describe P activities in the agricultural field. The objectives of this study were (1) to evaluate the accuracy and rationality of the RZWQM2-P model and improve its logic and algorithm; using the newly-developed RZWQM2-P model (2) to investigate the long-term P losses to tile drainage flow as affected by tillage and compost amendment in Harrow experimental site Ontario; (3) to figure out soil P level recovery ability from high manure amendment in Idaho site.

Four parts of the model algorithm received modification during simulation, including tillage mix efficiency, initial P pools partition, soil P dynamic and P stress. In the simulation of Harrow site, the model accurately simulated field-measured annual drainage water flow, as well as particulate P (PP) and total P (TP) losses in tile drainage, while underestimated dissolved reactive P (DRP) when organic wastes were applied. Long-term simulation results showed that an increase in tillage intensity (TI) and manure/compost P mix efficiency (ME) with soil by tillage decreased tile drainage flow and tile-drainage-borne P losses respectively. 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. In Idaho site simulation, the model well simulated field-measured annual soil total P ($P_{tot}$), plant P uptake ($P_{upt}$) and crop yield and acceptably simulated soil labile P ($P_{lab}$). Long-term simulation results showed that the soil needs to take 14 years to consume additional P from 8-year manure amendment on surface soil layers.

Overall, the modified RZWQM2-P model can accurately simulate most P loss through drainage though DRP loss prediction still needs to be improved, and the model simulated soil $P_{lab}$ and $P_{tot}$ completely at the first time and achieved satisfactory results. Therefore, it is crucial to determine the various best management practices (BMPs) to help substantially mitigate unnecessary phosphate consumption and the risk of P pollution.

# RÉSUMÉ

Bien que l'agriculture consomme 80 à 90% de la production annuelle et mondiale de phosphore (P), les plantes n'en utilisent efficacement que 20%, le reste étant rejeté dans l'environnement aquatique ou s'accumulant dans le sol. Le modèle RZWQM2-P a été nouvellement développé et ensuite intégré dans le modèle RZWQM2, fonctionnant comme un seul outil pour la description des activités du P dans les champs agricoles. Les Objectifs de cette étude étaient : (1) d'évaluer l'exactitude et la rationalité du modèle RZWQM2-P ainsi que d'améliorer sa logique et son algorithme en appliquant le modèle RZWQM2-P qui vient d'être développé ; (2) de rechercher les pertes de P à long terme dans le flux de drainage des tuiles affectées par la culture et l'amendement du compost dans le site expérimental de Harrow, Ontario ; (3) de découvrir la capacité de rétablissement du niveau de P du sol suite à un amendement élevé de fumier dans le site d'Idaho.

Les modifications apportées à quatre parties de l'algorithme du modèle ont été effectuées lors de la simulation, à savoir l'efficacité du mélange de culture, la répartition initiale des stocks de P, la dynamique du P du sol et le stress lié au P. En simulant le site Harrow, le modèle a simulé précisément le flux d'eau de drainage annuel enregistré sur le terrain, de même que les pertes de P particulaire (PP) et de P total (TP) dans le drainage par tuiles, tandis qu'il a sous-estimé le P réactif dissous (DRP) lors de l'application de déchets organiques. Selon les résultats de la simulation à long terme, l'augmentation de l'intensité de la culture (TI) et de l'efficacité du mélange de fumier et de compost (ME) avec le sol cultivé a respectivement réduit le flux de drainage des

tuiles et les pertes de P liées au drainage des tuiles. Plus précisément, lorsque TI est passé de 0 (sans labour) à 0,93 (Labour), le débit de drainage, les pertes de PRD et de PP ont diminué respectivement de 11,49%, 48,12% et 30,29%. De même, lorsque le ME est passé de 0 (pas de travail du sol) à 0,5 (disque tandem), les pertes de DRP et de PP à travers le drainage ont diminué respectivement de 53,98% et 30,95%. En ce qui concerne la simulation du site d'Idaho, le modèle a parfaitement simulé le P total annuel du sol enregistré sur le terrain ($P_{tot}$), l'absorption de P par les plantes ($P_{upt}$) et le rendement des cultures et a convenablement simulé le P labile du sol ($P_{lab}$). Les résultats de la simulation à long terme ont indiqué que le sol nécessite 14 ans pour absorber le P supplémentaire issu de l'amendement de fumier de huit ans dans les couches superficielles du sol.

En somme, le modèle RZWQM2-P modifié permet de simuler précisément la majeure partie de la perte de P par drainage, quoique la prédiction de la perte de DRP soit encore à améliorer, et le modèle a simulé complètement le sol $P_{lab}$ et $P_{tot}$ pour la première fois et a obtenu des résultats satisfaisants. En conséquence, il est vital de déterminer les différentes meilleures pratiques de gestion (MPG) en vue de contribuer à atténuer considérablement la consommation inutile de phosphate et le risque de pollution du P.

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# PREFACE AND CONTRIBUTION OF AUTHORS

This thesis contains title page, table of contents, brief abstract in both English and French, acknowledgement, list of tables and figures, abbreviations and symbols, major content, and references. The major content includes four chapters: Chapter 1-Introduction; Chapter 2-Modeling of Phosphorus Loss to Subsurface Drainage as Affected by Tillage Intensity under Compost Application; Chapter 3-Modification of RZWQM2-P model to simulate labile and total phosphorus in an irrigated and manure amended cropland and Chapter 4-Summary and Conclusion. There are connecting statements before Chapters 2&3.

Chapter 2 is a manuscript submitted to the Soil Tillage Research journal. The manuscript is co-authored by my supervisor Dr. Zhiming Qi, and Dr. Tiequan Zhang and Dr. Liwang Ma. Chapter 3 is a manuscript waiting for submitting to a journal and is currently reviewing by co-authors. The manuscript is co-authored by my supervisor Dr. Zhiming Qi, and Dr. Anita Koehn, Dr. April Leytem, Dr. Dave Bjorneberg and Dr. Liwang Ma.

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# CHAPTER 1 INTRODUCTION

## 1-1. GENERAL INTRODUCTION

Phosphorus (P) is one of the essential nutrient elements for determining agricultural productivity and supporting human and animal food (Hosseini et al., 2017; Smith et al., 2015). However, excessive P fertilization will increase P content in agricultural soil profile (Djodjic et al., 2004), raising the risk of P entering the aquatic environment, which causes water pollution and P waste. Soil P transformation and dynamics should be complex processes, integrating physical, chemical and biological processes that potentially occurred in root zone (Hinsinger, 2013; Messiga et al., 2015). Understanding the P changing regulation in soil profile will provide meaningful guidance for research work on controlling P pollution. Agricultural simulation models offer a convenient and low-cost method to indicate and quantify the potential pathway of P transfer (A. Vadas and J. White, 2010).

The Root Zone Water Quality Model 2 (RZWQM2) is a one-dimensional field-scale agricultural model integrating physical, chemical, biological and hydrological processes (Ahuja et al., 2000; Malone et al., 2004). The RZWQM2 model has been used to study the effects of management practices on hydrology, nitrogen balance, crop growth, energy balance and CO2 emission in several countries (Jiang et al., 2018; Liu et al., 2017; Ma et al., 2007; Qi et al., 2012). The RZWQM2-P model was newly developed to predict the fate and transfer in the agricultural field as a single tool (Sadhukhan et al., 2019a). There are three inorganic soil P pools, including labile P, active inorganic P and stable inorganic P, and two organic soil P pools, including stable organic P and fresh organic P, in the P model. The adsorption and desorption happen among inorganic P pools, the simulation based on Jones et al. (1984) with advanced dynamic as described by Vadas et al. (2006). While decomposition only occurs in organic P pools, mineralization and immobilization occur between organic P pools and labile P pool (Sadhukhan et al., 2019a). Among these P pools, labile P pool is the most active one and plants can absorb P from it directly. The equations from Neitsch et al. (2011) were employed to govern plant absorbed P from soil. When manure and fertilizer are applied to filed, the input P partition method adopted from Vadas (2014). The linear groundwater reservoir based approach (Steenhuis et al., 1997) was used to simulate dissolved reactive P (DRP), particulate P (PP) and total P (TP) loss through drainage. Sadhukhan et al. (2019b) demonstrated the good performance of RZWQM2-P in simulating DRP, PP and TP loss through runoff and drainage, then the model was applied to study the impact of three different management practices (controlled drainage, winter manure and injected manure application) on P loss.

## 1-2. OBJECTIVES

As for now, only limited researches have been conducted on the simulation of P losses from agricultural field using RZWQM2-P and there was no study finished complete simulation on soil P dynamic as its newly developed. Therefore, the objective of this study was to

(1) evaluate model performance in simulating DRP and PP loss through drainage against observed data in Ontario and analyze the impact of tillage practices on mitigating P losses.

(2) compare simulated soil labile P and total P content in soil profile with observed values in Idaho and investigate the time for consuming additional P from high manure application in soil.

(3) find and point out the weaknesses of the RZWQM2-P model during the simulation and do modifications to enhance the model performance.

# CONNECTING STATEMENT TO CHAPTER 2

In Chapter 2, the RZWQM2-P model was applied in simulating hydrology and P losses from an agricultural field, which include tile drainage flow, and dissolved reactive P, particle P and total P loss through drainage. The simulated results were compared with observed values collected in Harrow experimental site, Ontario and generally used model accuracy evaluation statistics were employed to evaluate the model performance. Meanwhile, the unreasonable part of the tillage algorithm in RZWQM2-P was fixed. The calibrated model scenario was then repeated to finish a long-term simulation to investigate the impact of tillage practices on P losses through tile drainage under compost amendment. The feature of tillage impact was subsequently discussed based on the simulated results.

Chapter 2 is a manuscript submitted to the Soil Tillage Research journal. The manuscript is co-authored by my supervisor Dr. Zhiming Qi, and Dr. Tiequan Zhang and Dr. Liwang Ma.

# CHAPTER 2. MODELING OF PHOSPHORUS LOSS TO SUBSURFACE DRAINAGE AS AFFECTED BY TILLAGE INTENSITY UNDER COMPOST APPLICATION


## 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) have helped substantially mitigate unnecessary phosphate applications. The objective of this study is to investigate tFhe 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 tillage intensity (TI, 0-1) and associated manure/compost P mix efficiency (ME, 0-1) with soil decreased tile drainage flow and tile-drainage-borne P losses. 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 main soil P dynamics 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.

## 2-1. 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 macro-nutrient in over 90% of major field crop fertilizers (al 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 and quickly depletion mineral resource and are expected to be exhausted within 70-140 years (Li et al., 2018). However, of the P used in fertilizer production, only 20% was taken up by plants (Cordell et al., 2009), the remaining being left in soils and may subsequently enter aquatic ecosystems and posing 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 the contaminated sources and recovering phosphorus from the wastewater. Currently, few phosphorus recovery technologies have been implemented in industry as most technologies are not profitable (Li et al., 2019a; Li et al., 2019b). 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 and 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 compost to improve plant growth and soil quality, as well as promoting resource recycling has met with some caveats (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 effect of soil amendment with organic waste on P loss, which can be achieved by a well calibrated computer model, however.

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 estuary waterways (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 is featured with a full set of tillage and manure options and has been verified using P 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, 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., 2004). 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., 2007; 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., 2007; Malone et al., 2003 and 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 model 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. Furthermore, the long-term effects of tillage on P loss from tile-drained fields amended with compost need to be quantified in addition to short-term field experiment. Therefore, the objectives of this study are: 1) to assess the performance of RZWQM2-P model in simulating tile drainage flow, DRP and PP losses from tile-drained plots with or without tillage and compost application, and 2) subsequently apply the model to quantify the long-term effect of tillage intensity (TI) and tillage mix efficiency (ME) on P losses through tile flow.

## 2-2. Materials and methods

### *2-2.1. Field experiment*

The observed data to calibrate/validate the RZWQM2-P model came from a field experiment conducted on two 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 ploughed 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 sizes 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 1 Jan. 1991 to 31 Dec. 2001 from the Woodslee weather station, located 1.5 km from the study field.

The treatments at both sites included a factorial combination of two compost treatments, 0 or 75 Mg dry weight (d.w.) $ha^{-1}$ ($CMP_0$ or $CMP_{75}$) and two tillage practices, no till and conventional (NT and CT), resulting in four treatment combinations $NT\text{-}CMP_0$, $NT\text{-}CMP_{75}$, $CT\text{-}CMP_0$, $CT\text{-}CMP_{75}$. 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 April each year.

The compost of tree leaves and other yard wastes were processed in a turned open-air windrow system (Essex-Windsor Solid Authority, ON, Canada) with a final C/N ratio approximately 15.5. While the properties of the compost produced in 2000 are not available, the data of 1998 was applied for 2000, as the compost was prepared following the same procedure using the materials from the same source, as well as the same crop was planted in these two years. The application rate and properties of the compost are listed in Information associated with compost and tillage are summarized in Table 2-1.

**Table 2-1. Details on tillage and compost application at both experiment farms.**

| Year | Crop | Compost | | | | | | | Tillage date | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Date | Rate (Mg d.w. $ha^{-1}$) | Organic matter (g $kg^{-1}$) | $NH_4$-N (g $kg^{-1}$) | P (g $kg^{-1}$) Total | P (g $kg^{-1}$) Water extractable | C: N | Mold-board | disk |
| 1998 | soybean | 10-Dec | 75 | 196 | 0.471 | 2.96 | 0.067 | 15.5 | 5-Nov | 10-May |
| 1999 | soybean | 21-Oct | 75 | 480 | 0.033 | 2.08 | 0.082 | 15.5 | 15-Oct | 2-May |
| 2000* | maize | 8-Dec | 75 | 196 | 0.471 | 2.96 | 0.067 | 15.5 | 15-Nov | 10-May |
| 2001 | soybean | No application after harvest | | | | | | | 20-Oct | 2-May |

* The properties of compost applied in 2000 are not available, the data of 1998 was use 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 2-A1.

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 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 and November 2001. This allowed for the collection of tile drainage samples on a flow-weighted basis using an ISCO model 2900 (Lincoln, Nebraska, USA) automatic samplers (Tan et al., 2002). 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.

### *2-2.2. 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 tile drainage under organic and inorganic P amendment, with details found in Sadhukhan et al.(2019a). The structure and dynamics of P pools are adopted from EPIC (Jones et al., 1984) and the decomposition processes of organic P in manure are from SurPhos model by Vadas (2014) (Figure 2-1A). In general, five P pools, stable inorganic, active inorganic, labile, fresh organic, and stable organic P, are created in the model to host all forms of P in soil. P in manure, when applied to the field, is partitioned into water extractable and stable inorganic and organic P pools. When inorganic or manure P is applied onto the surface of the field, tillage practices incorporate a fraction of surface manure water extractable inorganic P into soil labile P pool, and a fraction of surface manure inorganic stable P to soil active inorganic P pool. The fraction is determined using a parameter tillage mix efficiency. The other two surface manure P pools, manure water extractable organic P and manure stable organic P, though are incorporated into soil, will gradually mineralized into manure inorganic P pools.

However, in the 2019 version of RZWQM-P tillage mix efficiency was simply set as 1 minus tillage intensity (TI). Tillage intensity (0-1) indicates the percentage of stalk or manure residue on the surface being incorporated into the soil profile, while tillage mix efficiency (ME) is an indicator of how well the surface residue is mixed with soil. For some tillage method, i.e., moldboard plough, this relationship (ME = 1 – TI) approximately holds, because in moldboard plough, high fraction of residue is incorporated (0.95 for corn residue), while the mixing efficiency is low (0.25) as the residue was only flipped to bottom of the tilled soil layer. Whereas for many other tillage methods, i.e. tandem disk, this relation is not valid, as TI=0.75 but ME= 0.50 (values are mostly from GLEAMS). In our preliminary test in this study, we also found that it is difficult to simulate P losses to tile drainage water from P released from manure/compost at a very high rate. Therefore, we modify the model to use ME from GLEAMS (Knisel, 1993), not calculate from TI, to simulate P transfer 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, 1993), while TI values can be found from 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 follow:

$$LabP_a = LabP_b + (Avfertp + Resfertp + Manwip) * \frac{T_{mixeffi}}{100} \quad (1)$$

$$ActP_a = ActP_b + Mansip * \frac{T_{mixeffi}}{100} \quad (2)$$

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)

$ActP_a$=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 (%)

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)

### *2-2.3. Model Initialization, Calibration and Validation*

Data recorded for the management practices at two farms, 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 2-2. Parameters of the RZWQM2-P model was 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 $\text{CT-CMP}_{75}$ treatment was used to calibrate the model since it covered both management practices (tillage and compost application), while data from $\text{CT-CMP}_0$, $\text{NT-CMP}_0$, and $\text{NT-CMP}_{75}$ 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), a single parameter was varied at a time within a reasonable range based on the literature. 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 ($\lambda$) of the deeper soil layers (Table 2-2 and Table 2-3).

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

**model.**

| Soil layer | Initial Soil P | | Calibrated soil hydraulic parameters | | | |
|---|---|---|---|---|---|---|
| | Labile | Total | $P_b$ | λ | $k_{sat}$ | $k_{lat}$ |
| (m) | kg ha$^{-1}$ | kg ha$^{-1}$ | (kPa) | | (mm h$^{-1}$) | (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;.

The modified tillage component of the RZWQM2-P model was calibrated using soil P loss data. For the disking, effective depth was set at 10 cm with TI and ME calibrated to 0.4 and 0.5, respectively; for moldboard plow the depth was 15 cm, and model performed the best in simulating P release from compost with TI=1.0 and ME=0.25. As cracks presented ever year in the fields, the macroporosity was finally adjusted to 0.009 $m^3$ $m^{-3}$ to meet the level of PP lost in drainage flow. The manure and soil P parameters, including P extraction coefficient (P in manure extracted by rain), soil filtration, soil detachability and soil replenishment coefficient, were adjusted to 1, 0.1, 0.4 and 1, respectively, 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 (Sadukhan et al., 2019a) and the observed P losses in this study. The biomass P fractions at emergence, 50% maturity and maturity period were respectively set as 0.002, 0.001 and 0.0008, respectively, for maize, and 0.004, 0.002 and 0.001, respectively, for soybean. The P uptake distribution parameter of crop, a unitless parameter partitioning the weight of P adsorption in each soil layer in root zone, was adjusted to 5 for both maize and soybean. Values of the aforementioned parameters are listed in Table 2-3.

**Table 2-3 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 |
| 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 $ha^{-1}$) | 14 |
| 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 |
| 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 |

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 model is considered to perform satisfactorily when |PBIAS| is between 10%-15% for water flow and between 15%-30% for P, and it is deemed to be good when |PBIAS| is between 3%-10% for water flow and between 10%-15% for P. In terms of $R^2$, model performance is considered to be satisfactory when $0.6 < R^2 < 0.7$ and good when $0.7 \leqslant R^2 \leqslant 0.75$ for water flow and $0.40 < R^2 < 0.65$ and $0.65 \leqslant R^2 \leqslant 0.80$ for P simulation. For IoA, model performance is deemed to be acceptable when 0.75 < IoA < 0.85, and good when $0.85 \leqslant \text{IoA} \leqslant 0.9$ (Moriasi et al., 2015).

The original observed drainage flow and P loss data were sorted by periods as only one composite sample was analyzed for DRP and TP in a period. The periods roughly fell in a year was also grouped to an annual value for comparison. Sampling period and year delineation is shown in Appendix Table 2-A2.

### *2-2.4. Model Application*

The calibrated and validated RZWQM2-P model was then used to simulate the long-term effects of different tillage methods, represented by TI and ME (Table 2-4), 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 (Woodslee weather station) and management information from 1992 to 2018. Crop planting, chemical fertilizer and compost application and schedules from the calibrated scenario were repeated in long-term scenarios. All tillage effective depths were set to 0.15 m. Tillage methods after harvest were changed accordingly. TI & ME=0 represents no-till treatment. The row cultivator was set as the standard treatment and the simulated results from other tillage methods were compared to values from the row cultivator (TI=0.25 and ME=0.10) simulation, similar to the comparison conducted by Wang et al. (2022) using the EPIC model.

**Table 2-4. Tillage practices applied in RZWQM-P long-term simulation.**

| Implement name | Tillage intensity | Mix efficiency |
|---|---|---|
| No till | 0.00 | 0.00 |
| Paraplow | 0.20 | 0.05 |
| Row cultivator （Standard treatment） | 0.25 | 0.10 |
| Moldboard | 0.93 | 0.30 |
| One-way disk | 0.40 | 0.40 |
| Tandem disk | 0.50 | 0.50 |

## 2-3. Results

### *2-3.1. Annual Hydrology*

On an annual basis, the simulated tile drainage volume matched well with the observed drainage for all treatments (Table 2-5). For the calibration treatment $\text{CT-CMP}_{75}$, simulated tile drainage was satisfactory with PBIAS of -11.60%, IoA of 0.91, and $R^2$ of 0.76. For the validation treatments, simulated tile drainage showed high IoA values: IoA of 0.98 for $\text{NT-CMP}_{0}$, 0.96 for $\text{NT-CMP}_{75}$ and of 0.94 for $\text{CT-CMP}_{0}$, with $\text{NT-CMP}_{75}$ ranked as “good” with PBIAS of 5.01% and $R^2$ = 0.98, $\text{NT-CMP}_{0}$ and $\text{CT-CMP}_{0}$ “satisfactory” with PBIAS =-10.48% and 10.52%, respectively.

The simulated mean annual water balance is presented in Appendix A4.

Approximately, 16% of mean annual precipitation was lost through subsurface drainage, and precipitation loss through runoff accounted for 25.5%. Simulated evapotranspiration represented about 55% of mean annual precipitation with an average value of 46.22 cm per year. Predicted deep seepage averaged 1.05 cm, which accounted for about 1% of mean precipitation.

**Table 2-5. Model performance on simulating drainage flow and P losses and simulated P balance.**

| 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 | 99.33 | 103.98 | 83.82 | 93.56 |
| PBIAS | -11.60% | 5.01% | 10.52% | -10.48% |
| IoA | 0.91 | 0.96 | 0.94 | 0.98 |
| $R^2$ | 0.76 | 0.98 | 0.89 | 0.97 |
| | **DRP (g $ha^{-1}$)** | | | |
| Obs. mean | 181.62 | 361.83 | 45.89 | 57.38 |
| Sim. mean | 217.14 | 258.27 | 160.88 | 189.54 |
| PBIAS | 19.56% | -28.62% | 250.59% | 230.32% |
| IoA | 0.82 | 0.8 | 0.39 | 0.44 |
| $R^2$ | 0.59 | 0.67 | 0.48 | 0.15 |
| | **PP (g $ha^{-1}$)** | | | |
| Obs. mean | 347.11 | 323.32 | 274.1 | 361.73 |
| Sim. mean | 278.93 | 336.44 | 211.36 | 252.68 |
| PBIAS | -19.64% | 4.06% | -22.89% | -30.15% |
| IoA | 0.87 | 0.91 | 0.95 | 0.75 |
| $R^2$ | 0.81 | 0.76 | 0.99 | 0.5 |
| | **TP (g $ha^{-1}$)** | | | |
| Obs. mean | 555.32 | 760.92 | 331.38 | 433.6 |
| Sim. mean | 568.46 | 680.8 | 425.86 | 505.4 |
| PBIAS | 2.37% | -10.53% | 28.51% | 16.56% |
| IoA | 0.95 | 0.86 | 0.95 | 0.7 |
| $R^2$ | 0.95 | 0.8 | 1.0 | 0.35 |
| **P Components** | **P balance (kg $ha^{-1}$)** | | | |
| Manure P | 150 | 150 | 0 | 0 |
| Fertilizer P | 17.13 | 17.13 | 17.13 | 17.13 |

| | | | | |
|---|---|---|---|---|
| Residue P | 8.25 | 8 | 8.25 | 8 |
| Plant uptake P | 18.29 | 17.73 | 18.28 | 17.78 |
| DRP loss | | | | |
| Runoff | 5.88 | 11.84 | 0.65 | 1.34 |
| Drainage | 0.29 | 0.35 | 0.23 | 0.28 |
| PP loss | | | | |
| Runoff | 0.95 | 1.74 | 0.38 | 0.71 |
| Drainage | 0.35 | 0.43 | 0.28 | 0.35 |

### *2-3.2. Annual Drainage Phosphorus Losses*

Simulated and observed average annual DRP loss through tile drainage for calibration and validation treatments and associated model accuracy statistics (Table 2-5), show the simulation result of DRP loss through tile drainage to be satisfactory in the calibration phase, with the average annual simulated DRP loss averaging to be 217.14 g $ha^{-1}$ over four years, within a 19.56% bias of the observed value of 181.62 g $ha^{-1}$ (IoA = 0.82, and $R^2$ = 0.59). For the validation treatments, the simulation results of $NT\text{-}CMP_{75}$ was "satisfactory" (PBIAS within ± 30%, IoA > 0.75 and $R^2$ > 0. 40). However, the simulated results for $NT\text{-}CMP_0$ and $CT\text{-}CMP_0$ were unacceptable with the PBIAS values were more than 200%. Obviously, the RZWQM2-P model notably overestimated the DRP loss through tile drainage in this study.

Simulated PP loss in general matched well with the observed data. For the calibration treatment $CT\text{-}CMP_{75}$ the simulated annual PP loss was 278.93 g $ha^{-1}$, 19.64% lower than the observed average value 347.11 g $ha^{-1}$. The model accuracy statistics (IoA = 0.87 and $R^2$ = 0.81) showed a "satisfactory" agreement. For validation treatments, the model accuracy for $NT\text{-}CMP_{75}$ was "good", (PBIAS within ±10%, IoA > 0.90 and $R^2$ > 0.65) and for $CT\text{-}CMP_0$ was "satisfactory" (PBIAS within ± 30%, IoA > 0.75 and $R^2$ > 0. 40), while the accuracy was unacceptable for $NT\text{-}CMP_0$ with PBIAS = -30.15%

but very close to the threshold value of -30%. Similarly, the statistics of TP loss through tile drainage presented a good simulation. The calibration result showed a "very good" agreement in simulating TP with PBIAS of 2.37%, IoA of 0.95 and $R^2$ of 0.95. The simulation performance for validation treatments, $\text{NT-CMP}_{75}$ and $\text{CT-CMP}_0$, were deemed to be "good" and "satisfactory", respectively. However, the TP loss result of $\text{NT-CMP}_0$ 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 2-5. From the simulation result, no-till practices enhanced the DRP loss through both runoff and drainage compared to conventional tillage. Under $CMP_{75}$ and $CMP_0$ treatments, NT practice caused 50.34% and 51.49% increase, respectively, on the DRP loss through runoff than did the CT practice, and 17.14% and 17.86% rise on DRP loss through tile drainage. Similarly, the PP loss experienced about 45% decrease through runoff and 19% decrease through drainage under CT practice.

***2-3.3. Periodical Drainage and P Losses***

Table 2-6 presents the RZWQM2-P model performance rating measures when comparing the simulated drainage flow and P losses with the observed values grouped in periods instead of annually. The model performance on simulating tile drainage, DRP loss and PP loss were all unacceptable. The model cannot provide a good simulation result to match the observed data within a short time resolution. For example, when comparing the simulated drainage flow for all the periods with observed data, the PBIAS were the same as that obtained in the comparison of annual flow data, while $R^2$

was close to zero, and IoA lower than 0.6. Possibly, this poor fitting result was caused by improper simulation of winter drainage. The observed drainage in February was usually significantly underestimated and more drainage was rather postponed to March and April.

**Table 2-6. 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 | 0.42 | 0.36 | 0.54 | 0.34 |
| DRP loss | 0.24 | 0.18 | 0.19 | 0.21 |
| PP loss | 0.58 | 0.44 | 0.77 | 0.47 |
| | **$R^2$** | | | |
| | $CT\text{-}CMP_{75}$ | $NT\text{-}CMP_{75}$ | $CT\text{-}CMP_{0}$ | $NT\text{-}CMP_{0}$ |
| Tile drainage | 0.00 | 0.00 | 0.04 | 0.01 |
| DRP loss | 0.07 | 0.03 | 0.02 | 0.01 |
| PP loss | 0.04 | 0.00 | 0.38 | 0.08 |

### *2-3.4. Long-term Impacts of Tillage on P loss*

As illustrated in Fig. 2-1a, long-term simulation suggested that as TI increased, tile drainage volume, DRP and PP losses all decreased. When TI increased from 0.25 (rotary) to 0.93 (moldboard) tile drainage volume, DRP and PP losses decreased by 8.12%, 25.98%, and 8.79%, respectively; when TI decreased from 0.25 to 0.0 (no-till), tile drainage flow, DRP and PP losses increased by 4.63%, 26.8%, and 19.51%, respectively. In general, 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 the simulated effect of ME on P losses showed an evident decreasing trend as ME increased (Fig. 2-1b). Both ME and TI had a greater impact on DRP loss than PP loss. For example, when ME increased from 0.1 (rotary) to 0.5 (Tandem disk, Maximum ME in this long-term application), DRP and PP losses through tile drainage decreased by 23.87% and 11.17%, respectively. In general 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. As in RZWQM2-P model ME is only associated to phosphorus transfer among manure P pools, it does not affect drainage flow. Employing the same tillage methods and comparison strategy (using row cultivator as the baseline standard treatment), our study resulted in similar trend in Wang et al. (2022) in DRP loss under different ME values using EPIC model, in which strong negative relations were found between ME and DRP loss in tile drainage.

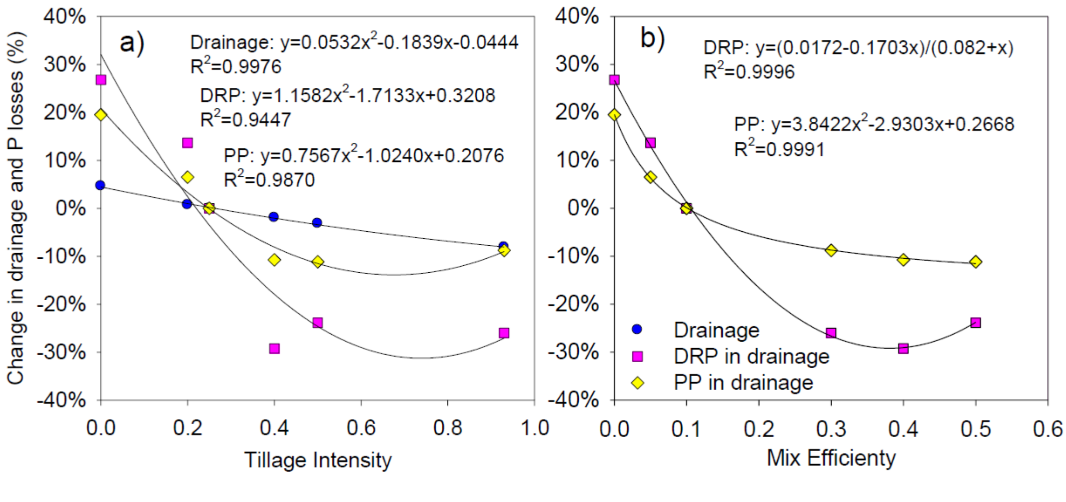



**Figure 2-1. Impact of a) tillage intensity (TI) on tile drainage, DRP and PP losses, and b) tillage mix efficiency (ME) on DRP and PP losses through drainage.**

## 2-4. Discussion

RZWQM2-P model performed well in simulating annual PP and TP losses to subsurface drainage as affected by tillage in the corn-soybean field amended with compost. Simulated DRP loss through tile drainage pointed out that the RZWQM2-P model underestimated the DRP loss when compost applied, suggesting that the RZWQM2-P model may greatly underestimate the DRP release from the compost. However, for now, parameters related to the rate of P mineralization from manure or compost is hard-coded in the model. In the next model version update, it worth trying to set manure mineralization rates adjustable. Some studies suggest that macropores are likely the essential flow pathway for P transport to subsurface drainage (Klaus et al., 2013; Williams et al., 2016). In the RZWQM2-P model, DRP and PP losses in tile drainage is 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).

In this study, we found that TI was negatively correlated to tile drainage volume (Fig. 2-1). Generally, the greater the TI, the lower the simulated bulk density in the tilled zone, indicating high soil porosity and water infiltration (Fig. 2-2a and b). Meanwhile tillage increases soil saturated hydraulic conductivity and resulted in higher soil evapotranspiration (Fig. 2-2c), which is also reported in Schwartz et al. (2010). Another reason is that less crop residues stayed on soil surface as the tillage intensity increased (Fig. 2-2d), which protects soil from crusting and sealing affected by rainfall and increases downward water flow in the soil (Stone and Schlegel, 2010). 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 reported 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. However, other management practices (e.g. ridge treatment) can also affect the experimental results. The influence of TI on tile drainage was relatively small compared to that of ME on soil P, which led to the change of P loss exceeds the change of tile drainage flow itself.

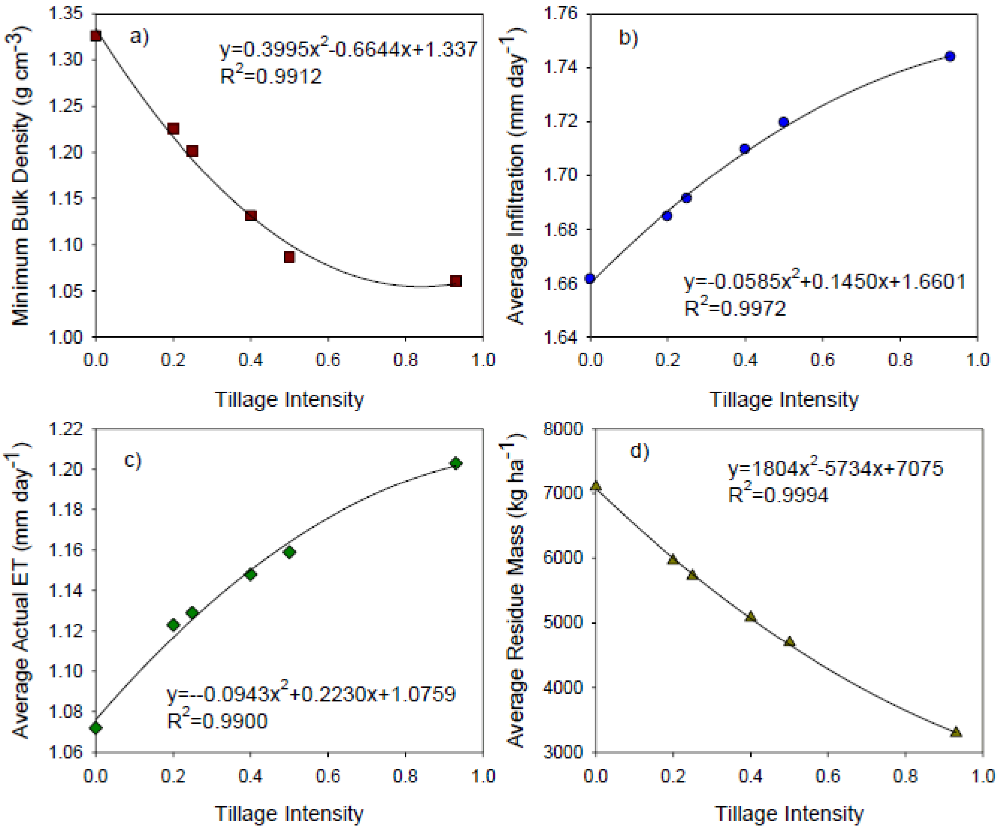



**Figure 2-2. Simulated effects of tillage intensity on a) soil bulk density, b) infiltration, c) soil evaporation, d) crop residue change after tillage.**

## 2-5. 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, while always underestimated DRP loss through tile drainage when compost applied. 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 the tillage effect on P losses in RZWQM2-P model still need to be further tested using more datasets.

## Appendix

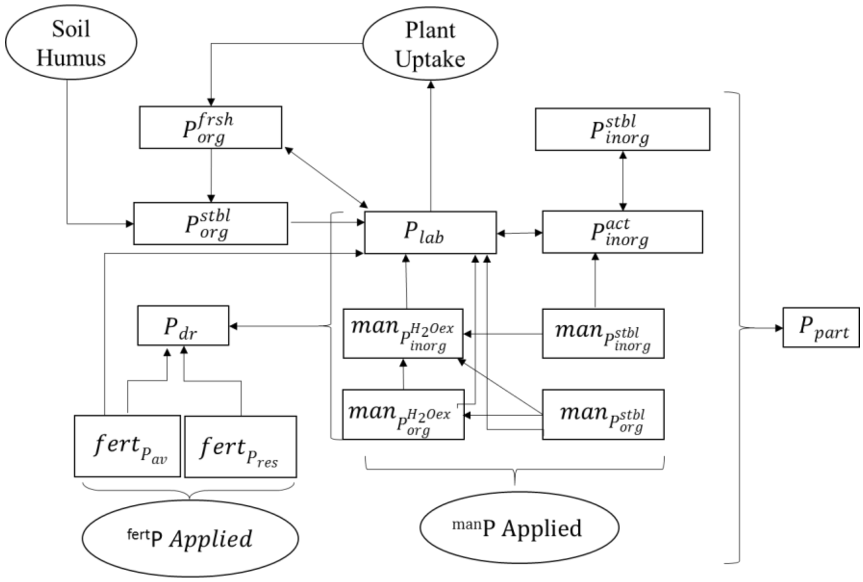



**Figure 2-A1. RZWQM2-P Model's P pools.**

$P_{org}^{frsh}$, fresh organic P; $P_{org}^{stbl}$, stable organic P; $P_{inorg}^{stbl}$, stable inorganic P; $P_{inorg}^{act}$, active inorganic P; $P_{lab}$, labile P pool; $^{man}P_{inorg}^{H_2Oex}$, manure water extractable inorganic P; $^{man}P_{inorg}^{H_2Oex}$, manure water extractable organic P; $^{man}P_{inorg}^{stbl}$, manure stable inorganic P; $^{man}P_{org}^{stbl}$, manure stable organic P; $^{fert}P_{av}$, available fertilizer P; $^{fert}P_{res}$, residual fertilizer P; $P_{dr}$,dissolved reactive P; $P_{part}$, particulate P; $^{fert}P$, fertilizer P; $^{man}P$, manure P.

**Table 2-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 2-A2. The correspondence between year and period of observed data**

| Year | Collection Period |
|---|---|

| | Start Date | End Date |
|---|---|---|
| 1998 | 9/15/1998 0:00 | 2/3/1999 |
| 1999 | 2/3/1999 0:00 | 3/8/1999 |
| | 3/8/1999 0:00 | 4/1/1999 |
| | 4/1/1999 0:00 | 4/14/1999 |
| | 4/14/1999 0:00 | 4/20/1999 |
| | 4/20/1999 0:00 | 4/27/1999 |
| | 4/27/1999 0:00 | 8/6/1999 |
| | 8/6/1999 0:00 | 4/25/2000 |
| 2000 | 4/25/2000 0:00 | 5/23/2000 |
| | 5/23/2000 0:00 | 6/26/2000 |
| | 6/26/2000 0:00 | 7/31/2000 |
| | 7/31/2000 0:00 | 8/9/2000 |
| | 8/9/2000 0:00 | 9/25/2000 |
| | 9/25/2000 0:00 | 10/12/2000 |
| | 10/12/2000 0:00 | 11/14/2000 |
| | 11/14/2000 0:00 | 12/20/2000 |
| | 12/20/2000 0:00 | 2/1/2001 |
| 2001 | 2/1/2001 0:00 | 2/14/2001 |
| | 2/14/2001 0:00 | 3/19/2001 |
| | 3/19/2001 0:00 | 4/4/2001 |
| | 4/4/2001 0:00 | 4/18/2001 |
| | 4/18/2001 0:00 | 5/15/2001 |
| | 5/15/2001 0:00 | 5/30/2001 |
| | 5/30/2001 0:00 | 8/21/2001 |
| | 8/21/2001 0:00 | 10/16/2001 |
| | 10/16/2001 0:00 | 11/14/2001 |

**Table 2-A3. Simulated and observed tile drainage flow (mm) and model accuracy statistics**

| Year | Calibration | | Validation | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $\text{CT-CMP}_{75}$ | | $\text{NT-CMP}_{0}$ | | $\text{NT-CMP}_{75}$ | | $\text{CT-CMP}_{0}$ | |
| | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. |
| 1998 | 52.30 | 0.00 | 10.40 | 0.00 | 25.83 | 0.00 | 19.84 | 0.00 |
| 1999 | 80.02 | 102.89 | 99.96 | 90.84 | 110.78 | 109.67 | 60.66 | 72.99 |
| 2000 | 175.11 | 145.49 | 148.86 | 151.61 | 127.53 | 159.67 | 125.66 | 125.85 |
| 2001 | 142.03 | 148.94 | 158.83 | 131.79 | 131.94 | 146.58 | 97.20 | 136.45 |
| Mean | 112.37 | 99.33 | 104.51 | 93.56 | 99.02 | 103.98 | 75.84 | 83.82 |
| PBIAS | | -11.60% | | -10.48% | | 5.01% | | 10.52% |

| | | | | |
|---|---|---|---|---|
| IoA | 0.91 | 0.98 | 0.96 | 0.94 |
| R2 | 0.76 | 0.97 | 0.98 | 0.89 |

**Table 2-A4. Average annual water balance (cm $day^{-1}$) simulated by the RZWQM2**

| Treatment | Rainfall | Infiltration | ET | Runoff | Drainage | Deep seepage |
|---|---|---|---|---|---|---|
| $CT\text{-}CMP_{75}$ | 84.03 | 62.31 | 45.57 | 21.33 | 14.05 | 1.51 |
| $NT\text{-}CMP_{75}$ | 84.03 | 60.17 | 43.59 | 23.47 | 14.72 | 0.58 |
| $NT\text{-}CMP_{0}$ | 84.03 | 62.04 | 46.46 | 21.60 | 13.67 | 0.64 |
| $CT\text{-}CMP_{0}$ | 84.03 | 64.40 | 49.27 | 19.24 | 12.50 | 1.47 |

**Table 2-A5. Simulated and observed DRP loss through tile drainage (g $ha^{-1}$) and model accuracy statistics**

| Year | Calibration | | Validation | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $CT\text{-}CMP_{75}$ | | $NT\text{-}CMP_{0}$ | | $NT\text{-}CMP_{75}$ | | $CT\text{-}CMP_{0}$ | |
| | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. |
| 1998 | 101.86 | 0.00 | 13.92 | 0.00 | 134.51 | 0.00 | 11.71 | 0.00 |
| 1999 | 76.77 | 198.50 | 8.08 | 187.79 | 142.57 | 230.55 | 28.59 | 137.45 |
| 2000 | 295.97 | 312.75 | 37.25 | 323.48 | 412.85 | 373.92 | 103.54 | 244.47 |
| 2001 | 251.89 | 357.33 | 170.28 | 246.92 | 757.40 | 428.60 | 39.70 | 261.58 |
| Average | 181.62 | 217.14 | 57.38 | 189.54 | 361.83 | 258.27 | 45.89 | 160.88 |
| PBIAS | | 19.56% | | 230.32% | | -28.62% | | 250.59% |
| IoA | | 0.82 | | 0.44 | | 0.80 | | 0.39 |
| $R^2$ | | 0.59 | | 0.15 | | 0.67 | | 0.48 |

**Table 2-A6. Simulated and observed PP loss through tile drainage (g $ha^{-1}$) and model accuracy**

**statistics**

| Year | Calibration | | Validation | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $CT\text{-}CMP_{75}$ | | $NT\text{-}CMP_0$ | | $NT\text{-}CMP_{75}$ | | $CT\text{-}CMP_0$ | |
| | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. |
| 1999 | 8.61 | 30.63 | 15.47 | 17.89 | 3.27 | 39.34 | 17.90 | 0.00 |
| 2000 | 340.27 | 384.99 | 351.58 | 418.50 | 298.12 | 466.54 | 362.09 | 306.23 |
| 2001 | 692.44 | 421.18 | 718.14 | 321.63 | 668.57 | 503.44 | 442.30 | 328.83 |
| Average | 347.11 | 278.93 | 361.73 | 252.68 | 323.32 | 336.44 | 274.10 | 211.36 |
| PBIAS | | -19.64% | | -30.15% | | 4.06% | | -22.89% |
| IoA | | 0.87 | | 0.75 | | 0.91 | | 0.95 |
| R2 | | 0.81 | | 0.50 | | 0.76 | | 0.99 |

The observed data for 1998 is not available.

**Table 2-A7. Simulated and observed TP loss through tile drainage (g ha$^{-1}$) and model accuracy statistics**

| Year | Calibration | | Validation | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $CT\text{-}CMP_{75}$ | | $NT\text{-}CMP_0$ | | $NT\text{-}CMP_{75}$ | | $CT\text{-}CMP_0$ | |
| | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. |
| 1999 | 85.38 | 229.13 | 23.56 | 205.68 | 145.83 | 269.89 | 46.50 | 137.45 |
| 2000 | 636.25 | 697.74 | 388.83 | 741.97 | 710.96 | 840.46 | 465.63 | 550.71 |
| 2001 | 944.32 | 778.50 | 888.42 | 568.55 | 1425.97 | 932.05 | 482.01 | 589.41 |
| Average | 555.32 | 568.46 | 433.60 | 505.40 | 760.92 | 680.80 | 331.38 | 425.86 |
| PBIAS | | 2.37% | | 16.56% | | -10.53% | | 28.51% |
| IoA | | 0.95 | | 0.70 | | 0.86 | | 0.95 |
| R2 | | 0.95 | | 0.35 | | 0.80 | | 1.00 |

# CONNECTING STATEMENT TO CHAPTER 3

In this chapter, the RZWQM2-P model was used to simulate soil P dynamic in an irrigated and manure amended cropland in Idaho. The model was calibrated to predict labile P and total P in soil profile, plant P uptake and crop yield against field experimental data. Meanwhile, the illogical parts on P pools partition and P stress were modified during simulation period. As experimenters suggested, the model application studied the time for the soil to recover to the initial P level after high manure was applied. Ultimately, model performance and soil P content change during recovery were discussed to reveal soil P dynamic behaviour.

Chapter 3 is a manuscript waiting for submitting and is currently reviewing by co-authors. The manuscript is co-authored by my supervisor Dr. Zhiming Qi, and Dr. Anita Koehn, Dr. April Leytem, Dr. Dave Bjorneberg and Dr. Liwang Ma.

# CHAPTER 3 MODIFICATION OF RZWQM2-P MODEL TO SIMULATE SOIL LABILE AND TOTAL PHOSPHORUS IN AN IRRIGATED AND MANURE AMENDED CROPLAND


## Abstract

With the expansion of dairy industry, phosphorus (P) enriched dairy manure was increasingly used to replace chemical fertilizer to meet crop nutrients demand, which would lead to excessive total P accumulation in the soil and increase the risk of P pollution. The newly-developed RZWQM2-P model used the soil P pool structure from EPIC which is not sensitive to soil total P. In this study we modified the RZWQM2-P model to facilitate the model in simulating soil total P. We subsequently assessed the modified model in simulating soil labile P, soil total P, plant P uptake, and crop yield using a dataset collected from an irrigated dryland corn field treated with dairy manure and inorganic fertilizer of 8 rates, and simulated the long-term soil P dynamics under three P application scenarios. The results suggests that the modified RZWQM2-P model well simulated field-measured annual soil total P, plant P uptake and crop yield. Soil labile P result was less accurate but acceptable as it simulated well for most of the treatments. Long-term simulation results showed the soil took 14 years to reduce $P_{lab}$ to initial level after 8-year manure P applied with a rate of 65.5 kg P ha$^{-1}$ year$^{-1}$. This study concludes that the modified RZWQM2-P model can be used to simulate soil total P and labile P content in irrigated dryland field and to assess P management practices under dryland agriculture.


## 3-1. Introduction

Dairy industry will continue to grow in order to supply the growing protein demand of consumers (Hill et al., 2021). Idaho is the third-largest dairy industry state in the United States

(Lauer et al., 2018). However, the development of dairy industry has brought some problems, including waste disposal, while promoting the local economy (Cabrera et al., 2009). Dairy manure was increasingly used to replace chemical fertilizer as a source of nutrients to meet crop growth requirements of N and P due to the expansion of the milk-producing industry in southern Idaho (Leytem et al., 2011). Although the application of manure can not only recycle nutrients and waste from animal feeding but also help enhance soil fertility, manure may lead to P accumulation in the soil and become non-point source pollution to the aquatic system (Obi and Ebo, 1995; Wang et al., 1996; Weyers et al., 2016). Meanwhile, of the P used in crop nutrients production, only about 20% was assimilated by plants (Cordell et al., 2009). Therefore, trying to plan the P application through manure and fertilizer rationally is vitally crucial for saving P resources, keeping soil healthy, and reducing agricultural pollution. Evaluating the impact of long-term high fertilization on the soil P dynamic parameters would in favor of building up fertilization strategy (Chen et al., 2022). However, field researches on nutrient reduction strategies are limited to a narrow range of time period, soil types and specific treatments (Craft et al., 2018; Tuppad et al., 2010). Agricultural modeling tools are able to investigate the effects of high fertilization on soil P dynamic by extending beyond the constraints of field research.

The Root Zone Water Quality Model 2 (RZWQM2) is a one-dimensional field-scale agricultural model, integrating physical, chemical, biological and hydrological processes (Ahuja et al., 2000). The RZWQM2 model has been world-widely used to study hydrology, nutrients dynamics, crop growth and greenhouse gas emission (Jiang et al., 2018; Liu et al., 2017; Ma et al., 2007; Qi et al., 2012). The P module was recently developed using the EPIC P frame (Jones et al., 1984) and most recently updated sciences in P cycling (i.e. Vadas, 2014), and was subsequently incorporated into the RZWQM2 model to create a RZWQM2-P model which simulates P dynamics in soil, plant, and water (Sadhukhan et al., 2019a). The RZWQM2-

P model has been successfully used to predict the loss of different P forms, including dissolved reactive P (DRP), particulate P (PP) and total P (TP), through tile drainage flow in subhumid regions. However, EPIC P frame, widely adopted in many P models, is not designed to address the dynamics of total P in soil. Therefore, the first objective of this study is to improve RZWQM2-P's capability in simulating the dynamics of total P in soil through modifying the EPIC P frame. In addition, RZWQM2-P model has never been used to predict soil P dynamics (i.e. labile and total P) in irrigated dryland agriculture in which the P management practices needs to be urgently assessed. Hence, the second objective is to assess the modified RZWQM2-P using soil labile P and total P data collected from an irrigated corn field amended with various P fertilization rates and then to quantify soil P recovery behaviour under different P management strategies.

## 3-2. Materials and methods

### *3-2.1 Field experiment*

The observed data used to calibrate the RZWQM2-P model were collected from the experimental fields located at the USDA-ARS Northwest Irrigation and Soils Research farm near Kimberly, ID (lat. 42° 33′ N, long. 114° 21′ W). The field experiment started in the fall of 2012 and had a five-year crop rotation of spring wheat (2013)-potato (2014)-spring barley (2015)-sugar beet (2016)-spring wheat (2017). Crop management parameters are given in Table 3-1.

**Table 3-1. Planting parameters for the scenarios in the RZWQM2.**

| Year | Crop | Planting date | Density | Row spacing | Harvest date |
|---|---|---|---|---|---|
| | | | plants ha$^{-1}$ | cm | |
| 2013 | spring wheat | 02 April | 2209000 | 18 | 13 August |
| 2014 | potato | 29 April | 35625 | 91 | 10 September |
| 2015 | spring barley | 31 March | 2209000 | 18 | 29 July |
| 2016 | sugar beet | 09 May | 82200 | 22 | 11 October |
| 2017 | spring wheat | 05 April | 2209000 | 18 | 15 August |

The experiment followed completely randomized block design, with individual plot sizes of 12.2 × 18.3 m. There was a total of eight treatments in this experiment and each treatment have four replications. The treatments included no chemical fertilizer or manure (noted as Control), chemical fertilizer only (noted as Fertilizer), dairy manure applied annually at six specific rates (18T_A, 36T_A & 52T_A, the digit represents the manure rate in "tons/ha" and "A" represents "Annually") and dairy manure applied biennially the same rates (18T_B, 36T_B & 52T_B, "B" represents "Biennially"). In order to maximize the 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 in manure and inorganic fertilizer application are listed in Table 3-2 and Table 3-3, respectively. After manure was applied, it was immediately incorporated into soil through disking; the fertilizer and control treatments were disked at the same time as well. All treatments were irrigated using sprinklers with 41.05 cm for wheat in 2013, 59.31 cm for potato in 2014, 34.16 cm for barley in 2015, 72.62 cm for sugar beet in 2016, and 57.43 cm for wheat in 2017.

**Table 3-2. Manure application time, rate, and properties.**

| Treatment<br>Year | Applied date | Manure<br>kg ha$^{-1}$ | $NH_4^+$-N<br>kg ha$^{-1}$ | Total N<br>kg ha$^{-1}$ | P<br>kg ha$^{-1}$ | C:N | Fraction of Carbon |
|---|---|---|---|---|---|---|---|
| **18T_A,B** | | | | | | | |
| 2013,A | 06 November | 22587 | 64.08 | 420.12 | 140 | 17.45 | 0.325 |
| 2014,A | 23 October | 20000 | 43.78 | 196.86 | 67 | 15.61 | 0.181 |
| 2014,B | 23 October | 16970 | 37.12 | 232.15 | 67 | 15.13 | 0.159 |
| 2015,A | 22 October | 19000 | 52.64 | 267.99 | 128 | 14.54 | 0.210 |
| 2016,A | 16 November | 17248 | 60.48 | 281.12 | 96 | 14.80 | 0.187 |
| 2016,B | 16 November | 17248 | 60.48 | 281.12 | 125 | 15.80 | 0.212 |
| **36T_A,B** | | | | | | | |
| 2013,A | 06 November | 44000 | 124.78 | 809.84 | 265 | 16.97 | 0.312 |
| 2014,A | 23 October | 41000 | 88.66 | 478.25 | 139 | 15.79 | 0.187 |
| 2014,B | 23 October | 36640 | 88.66 | 432.35 | 139 | 15.79 | 0.187 |
| 2015,A | 22 October | 39000 | 106.40 | 563.28 | 258 | 14.16 | 0.204 |
| 2016,A | 16 November | 34720 | 122.08 | 566.72 | 251 | 16.10 | 0.192 |
| 2016,B | 16 November | 34720 | 122.08 | 566.72 | 251 | 16.20 | 0.199 |
| **52T_A,B** | | | | | | | |
| 2013,A | 06 November | 70000 | 199.07 | 1298.15 | 423 | 16.63 | 0.308 |
| 2014,A | 23 October | 55494 | 121.39 | 699.22 | 203 | 15.79 | 0.199 |
| 2014,B | 23 October | 58000 | 126.42 | 728.19 | 203 | 16.14 | 0.214 |
| 2015,A | 22 October | 58000 | 160.16 | 829.76 | 386 | 15.07 | 0.217 |
| 2016,A | 16 November | 51968 | 183.68 | 848.96 | 376 | 15.90 | 0.191 |
| 2016,B | 16 November | 51968 | 183.68 | 848.96 | 376 | 14.80 | 0.194 |

Letter "A" after the year represents manure applied on an annual basis (once in a year) and "B" represents biennial basis (once in two years).

**Table 3-3. Inorganic fertilizer (N and P) application time and rate.**

| Year | Crop | Applied date | 18T_A | 18T_B | 36T_A | 36T_B | 52T_A | 52T_B | Fertilizer |
|---|---|---|---|---|---|---|---|---|---|
| | | | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | 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 |

"--" means no corresponding nutrient applied.

The soil was a Portneuf silt loam (USDA-NRCS, 2016). Soil samples were collected annually after harvest and prior to manure application (Sep. 25-26, 2012; Sep. 30, 2013; Oct. 9, 2014; Sep. 24, 2015; Nov. 15, 2016; and Sep. 18, 2017) from every plot at the depths of 0-15, 15-30, 30-60, 60-90, and 90-122 cm. After collection, soil samples were sent to the laboratory to analyze 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). Phosphorus in the extracts obtained from the Olsen-P method was determined by the ascorbic acid colorimetric method (Frank, 1998; Murphy and Riley, 1962) using a Skalar spectrophotometer (Skalar Analytical B.V., Breda, Netherlands). For analyzing soil total P, 0.25 g dried soil samples were digested by microwave-assisted digestion with concentrated $H_2SO_4$ and HCl, and 30% $H_2O_2$ and determined by ICP-OES (PerkinElmer Optima 4300 DV, Wellesley, MA) detection (US-EPA, 1996). 0.5 g dried plant samples were digested with concentrated $HNO_3$ and HCl, and 30% $H_2O_2$ and the same microwave-assisted digestion method for soil total P to measure plant P uptake.

***3-2.2 Model description and modification***

RZWQM2 (Root Zone Water Quality Model) is a one-dimensional process-based model integrating physical, biological, chemical, and hydrological processes in agricultural production systems (Ahuja et al., 2000) that has been widely used to study hydrology, water quality, crop growth and nutrients transportation (Liu et al., 2017; Ma et al., 2007; Qi et al., 2012; Sadhukhan et al., 2019b). The RZWQM2 employs the Brook-Corey equations (Brooks and Corey, 1964) for soil water retention. The 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 happens when the rainfall rate exceeds the infiltration rate and the sediment yield is calculated using the Universal Soil Loss Equation (Wischmeier and Smith., 1978). DSSAT crop growth model (Jones et al., 2003) was incorporated into RZWQM2 for a better simulation of crop yield. Recently a phosphorus module is incorporated in therefore the RZWQM2-P model was newly developed to simulate the fate and transport of P in the soil-plant-water system, in particular for dissolved and particulate P losses in tile drained field (Sadhukhan et al., 2019a). Following Jones et al. (1984), the RZWQM2-P model 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 for plant growth can only be absorbed from the labile P pool, and the plant P uptake subroutine is adopted from Neitsch et al. (2011). The delineation and dynamics of labile, organic and inorganic soil P pools are adopted from the EPIC model by (Jones et al., 1984), while the phosphorus absorption, desorption, and decomposition rate of surface residue and manure are adopted from the SurPhos model by Vadas et al. (2006). The distribution method of manure P and fertilizer P in soil profile comes from Vadas et al. (2007) and Vadas (2014).

The RZWQM2-P model was proved 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 in simulating labile and total P pools in the soil due to the lack of continuous measurement of those two soil P pools in most cases. Recently, we were introduced to a dataset from USDA-ARS Northwest Irrigation and Soils Research Unit at Kimberly, Idaho, USA, in which labile and total P pools were measured continuously from 2012 to 2017 for 6 soil layers from 0-154 cm under various manure and fertilizer P application rates.

Our preliminary test showed that, when initializing P pools, the fixed ratio of stable inorganic and active inorganic P, set at a fixed value of 4 as adopted from EPIC by Jones et al. (1984), would result in an unclosed total P. This would explain why in Jones et al. (1984) it is stated that the EPIC model "model is insensitive to pool sizes of stable inorganic P and total soil P". As in this dataset no yield loss was found only due to P stress, but we found the P stress method adopted from Neitsch et al. (2011) was not properly structured in P module as no yield loss when P stress existed. Therefore, methods were found to fix those problems and changes of the code for the P module of RZWQM2-P were made as follows.

**Stable and active inorganic P ratio**

To fix the problem of P initialization, we changed the fixed ratio of 4 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:

$$Ratio = \frac{P_{inorg}^{stab}}{P_{act}} \quad (1)$$

For stable inorganic P, it can be computed using the equation below:

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

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 of all P pools are kg $ha^{-1}$.

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

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

PSP is P sorption coefficient (or P availability index, unitless) which can be computed using (Williams et al., 2008):

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

Where Clay is the percent of clay in soil (i.e. 20 for a loam soil), SoilOC is the percent of soil organic carben content (i.e 1.50 for a soil with medium soil organic carbon content). Stable organic P ($P_{org}^{stab}$) can be estimated using the total soil carbon and assumed C:P ratio of 100:

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

Where SOM is soil organic matter content (%, i.e. 3.0 for a soil) and soil mass is the mass of soil in a soil layer (kg/ha).

**Crop P stress**

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

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

Where,

$Bio_{p,act}$ is actual plant P uptake in one day (kg/ha),

$Bio_{p,opt}$ is optimum mass of P that should be adsrobed by plant biomass in that day (kg/ha).

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

***3-2.3 Model initialization and partition of P pools***

The P simulation scenarios used in this study were adopted from Koehn et al. (2021) which simulated soil nitrogen dynamics of this site using RZWQM2. 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. organic matter, residue pools and microbial population) remain unchanged. The measured $P_{lab}$ (Olsen-P) and $P_{tot}$ (total P) data in 2013 is used to initialize the soil P pools. Model input soil P data is presented in Table 3-4.

When setting soil initial 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, inputting observed $P_{lab}$ values to RZWQM2-P model interface while keeping other initial P pools as 0, then run the model and the model will calculate the corresponding $P_{act}$ values according to equation (3), as PSP will be computed by the model using SOC, soil clay content, and liable P in soil. The $P_{act}$ calculation results can be found in SoilP output file. Then users are required to calculate $P_{org}^{stab}$ and $P_{inorg}^{stab}$ using equation (5) and (2). P in fresh organic matter ($P_{org}^{frsh}$) in tillage depths can be computed using the mass of soil residue (usually a few tons/ha) multiplied by residue P content (usually 1/10 of N content or approximately 0.2%). Finally, 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 3-5 presented initial P pools partition of 52T_A and Control treatments as example.

**Table 3-4. Input soil initial labile P and total P used for the scenarios in the RZWQM2.**

| Soil layers | 18T_A | 18T_B | 36T_A | 36T_B | 52T_A | 52T_B | Control | Fertilizer |
|---|---|---|---|---|---|---|---|---|
| cm | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ |
| Labile P (Olsen-P) | | | | | | | | |
| 0-15 | 51.71 | 75.98 | 84.39 | 110.08 | 157.94 | 124 | 34.34 | 41.3 |
| 15-30 | 12.23 | 15.88 | 11.9 | 14.83 | 19.19 | 16.65 | 9.58 | 8.81 |
| 30-60 | 7.29 | 8.55 | 10.4 | 9.67 | 8.36 | 9.29 | 7.7 | 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 | 9.8 | 13.38 |
| 120-154 | 37.1 | 19.91 | 27.89 | 44.53 | 38.03 | 26.23 | 26.32 | 36.37 |
| Total | 130.15 | 140.34 | 192.98 | 211.8 | 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 | 14099 | 14376 | 14474 | 15025 | 14044 | 14906 | 13881 | 14453 |

18,36,52 means applied manure amounts were approximately equal to 18, 36 and 52 t ha$^{-1}$ respectively; A and B means applied manure annually and biennially respectively.

**Table 3-5. Initial P pools partition in 52T_A and Control scenarios.**

| Soil depth | SOM | PSP | $P_{lab}$ | $P_{tot}$ | $P_{act}$ | $P_{inorg}^{stab}$ | $P_{org}^{stab}$ | $P_{org}^{frsh}$ | $\frac{P_{inorg}^{stab}}{P_{act}}$ Ratio |
|---|---|---|---|---|---|---|---|---|---|
| cm | % | | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | |
| **52T_A** | | | | | | | | | |
| 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 |

SOM is the percent of 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.

The P simulation results can be found in 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 daily and annual basis, while the P content in different P pools only given on a daily basis and presented layer by layer, which means the total amount of a specific format P (i.e. $P_{lab}$, $P_{act}$, $P_{inorg}^{stab}$, $P_{org}^{stab}$ and $P_{org}^{frsh}$) needs to be added up for each layer to get total P.

### *3-2.4 Model calibration and validation*

As soil P was measured annually (once in each year in 2013-2017) and there were 8 treatments in this study, we used data from 4 treatments in all years for calibration, and the rest 4 treatments for validation, following the suggestion of using multiple treatments in multiple years for calibration in Ma et al. (2012). Usually the plots with no or least nutrient and water stress should be used for calibration as 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, Table 3-2 and 3-3) was sufficient for crop growth. Therefore, the treatments of 18T_A, 18T_B, 36T_A and 36T_B were used to calibrate the model, while the data from 52T_A, 52T_B, Control and Fertilizer were used for validation.

Soil and crop parameters related to phosphorus in the model were calibrated against observed total soil P ($P_{tot}$), soil labile P ($P_{lab}$) and plant P uptake ($P_{upt}$) without hampering 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 3-6 were calibrated against crop P uptake data. In this study, DSSAT sugar beet model in RZWQM2-P was used instead of original HERMES sugar beet used by Koehn et al. (2021), as for now only DSSAT crop model was linked to the phosphorus module of

RZWQM2-P model. The crop growth parameters for DSSAT sugar beet are calibrated using the observed sugar beet biomass (Table 3-6).

**Table 3-6. Calibrated plant P parameters for wheat, barley, potato and sugar beet and plant biomass parameters for sugar beet used in the 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 seeding emergence to the end of the juvenile phase (°C days)
P2 = Delay in development for each hour that daylength is above 12.5 hours (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 = Phylochron interval; the interval in thermal time (°C days) between successive leaf tip appearances

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

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

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

Where $O_i$ is the observed value; $P_i$ is the simulated value for the observed value; $\bar{O}$ and $\bar{P}$ are the mean of observed and simulated values respectively; $n$ is the total number of observations. PBIAS reflects whether the simulation results are greater or lesser than 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| is within 30% and $R^2 > 0.4$ for P, good when |PBIAS| is between 10-15% and $0.60 \leq R^2 \leq 0.80$ and very good when |PBIAS| is between 0-10% and $R^2 > 0.80$.

#### *3-2.5 Model application*

The calibrated and validated RZWQM2-P model was then used to simulate three long-term (24-year, 1993-2017) scenarios with the rotation of potato-barley-sugar beet-spring wheat. Three long-term scenarios were designed with continuous treatment, recovery treatment and control_lt (note: lt means long-term) treatments. In the continuous treatment, the 52T_A manure and fertilizer application rates (52 tons $ha^{-1}$ manure which contains 376 kg $ha^{-1}$ P every year) was applied for all 24 years; while in recovery treatment, 52T_A manure application rate was repeated for 8 years and then terminated P input for the rest 16 years. For the control_lt treatment, no P was applied to the field for 24 years so only initial P data from validated Control treatment was used to support crop growth. The goal of this model application was to figure out how many years it would take to consume exceed input P in soil after repeated high manure applications. Four-year weather from calibrated scenarios was repeated eliminate the variability in the results, following the same warm-up strategy used in Kohen et al (2021).

## 3-3. Results

#### *3-3.1 Total P in soil profile*

The model performance was satisfactory in simulating $P_{tot}$ in different soil layers (Table 3-7) as indicated by PBIAS and $R^2$ values for all treatments. For four calibration treatments (18T_A, 18T_B, 36T_A, and 36T_B), the overall model performance when comparing simulated with observed total P in all soil layers across all years fell in the "very good" category (|PBIAS| within 10% and $R^2 > 0.8$). For those four validation treatments (52T_A, 52T_B, Control, and Fertilizer), the overall model performance for 52T_B and Fertilizer were "very good" as well with PBIAS within6.0%, and $R^2 > 0.8$ ; similarly, the overall model performance in 52T_A and Control treatments showed "good" where PBIAS were -12.19% and 12.03% respectively, and $R^2 > 0.8$. Generally, the RZWQM2-P model tended to underestimate $P_{tot}$ in the soil, -8.72% to -0.79% less for 2014 and -15.54% to -7.71% less for 2017, except the 18T_A treatment, where the model simulated $P_{tot}$ content was 13.84% higher than the observed for 2014 and 4.76% higher for 2017.

When comparing the $P_{tot}$ data in soil profile from 2017 (Fig. 3-1), the simulated $P_{tot}$ only changed in the top two soil layers rather than deep layers, because in the model applied P was constrained in the top three soil layers and for deeper soil layers there is no additional input or output therefore no transfer among P pools. It also suggested that in the model there might be no movement of soluble P from top soil layers down with soil water or the downward P flux as a result of soil water movement below 30 cm in the soil profile was negligible in this dryland field, in particular when the total P was several orders of magnitude higher than soluble or plant available P. The observed total P in the 0-122 cm soil profile ranged from 11079 kg/ha in the Control in 2013 to 14267 kg/ha in 52T_A in 2017. Although the downward movement of P flux was not measured in this field, our previous experience showed that the P flux to tile drainage in sub-humid climate with intensive P application was about 0.4 kg $ha^{-1}$ (Zhang et al., 2017). However, the observed $P_{tot}$ in deep soil layers did not vary much over time either, only with an average increase of 6%. Therefore, the modeling strategy in simulating total P is successful though the downward movement of soluble P needs further test.

**Table 3-7. The model accuracy statistics of total P in the year of 2014 and 2017 and overall total P.**

| Year | PBIAS | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Calibration | | | | Validation | | | |
| | 18T_A | 18T_B | 36T_A | 36T_B | 52T_A | 52T_B | 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 |

### *3-3.2 Plant available P in soil profile*

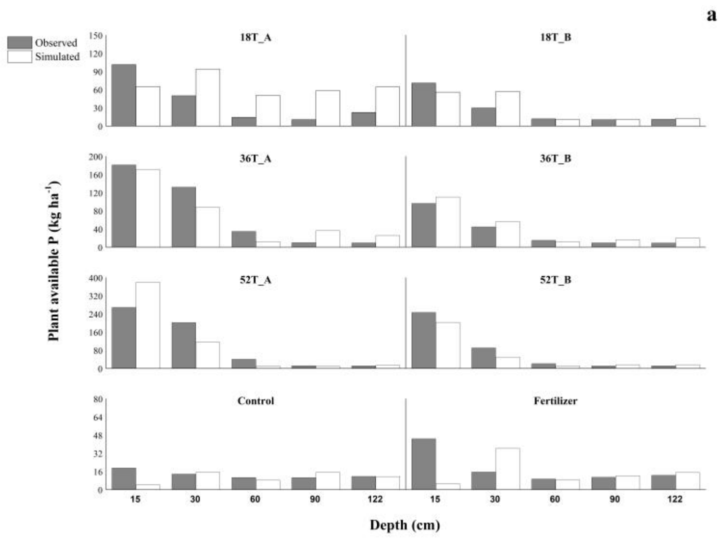
Table 3-8 showed four years (2014-2017) of statistical results of overall and individual soil layers $P_{lab}$. The overall model performance in simulating $P_{lab}$ in the soil is acceptable (PBIAS within ±30% and $R^2$>0.4) when compared with the observed $P_{lab}$ data for most treatments. In the calibration treatments, the annual $P_{lab}$ simulation result of 36T_A was "very good", with a -8.83% PBIAS from the observed value of 275.58 kg $ha^{-1}$ and $R^2$ = 0.84. The annual simulated $P_{lab}$ of 18T_B was 132.25 kg $ha^{-1}$, 18.39% higher than the observed values. However, for treatment 18T_A, the PBIAS and $R^2$ for $P_{lab}$ simulation were 55.54% and 0.07, versus 14.55% and 0.37 for 36T_B treatment, which were unacceptable according to Moriasi et al. (2015). For validation treatments, the statistic results of 52T_A were "very good" (PBIAS within ±10% and $R^2$ > 0.80) and for 52T_B and Control treatments were "satisfactory" (PBIAS within ±30% and $R^2$ > 0.40). The annual $P_{lab}$ predictions were 8.24% bias of the observed values for Fertilizer treatment, however, the $R^2$=0.12 resulted in unsatisfactory model simulation result.

Table 3-8 also suggests that, when comparing simulated soil labile P in all layers with observed data in each year, the model performance can be also treated acceptable with PBIAS within ±30% in more than 78% cases and $R^2$ > 0.40 in more than 80% cases. The majority of the simulation failure occurred in 18T_A and Fertilizer treatments in which P input was relatively low. For those low and no P input treatments (i.e. Control and Fertilizer), the simulated labile P in the top soil layer (0-15 cm) was significantly underestimated (Fig. 3-1). It is because that the P depletion was only set for the top soil layers. This insufficiency of this strategy is not visible when P input or mineralized soil P is high; however, under a situation of those P sources are very limited (i.e. Control, and Fertilizer in this study), the soil profile depth for P assimilation by plant root should be set the same to the rooting depth to reduce P depletion in the top layers. However, the total labile P in the whole soil profile was not affected by the mismatch of labile P in the top soil layers.

**Table 3-8. The model accuracy statistics of labile P in the year of 2014, 2015, 2016 and 2017 and annual average labile P.**

| | PBIAS | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Year | Calibration | | | | Validation | | | |
| | 18T_A | 18T_B | 36T_A | 36T_B | 52T_A | 52T_B | 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 show unsatisfactory statistic results.



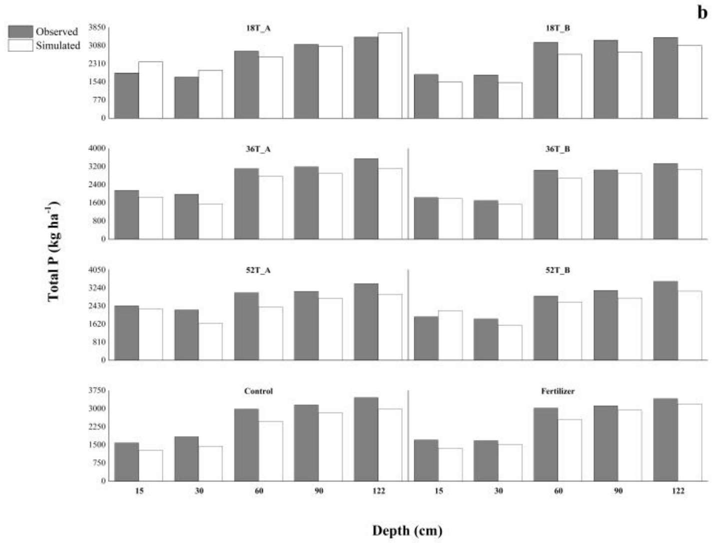



**Figure 3-1. Simulated and observed $P_{lab}$ (a) and $P_{tot}$ (b) on 18 September, 2017**

### *3-3.3 Plant uptake P and crop yield*

Predicted $P_{upt}$ matched well with the observed data (Table 3-9), with the statistic results, PBIAS and $R^2$, all in the acceptable range except for the Control treatment. For calibration treatments, the model accuracy statistics showed "very good" agreement for 36T_A treatment with PBIAS = -8.84% and $R^2$ = 0.99 and "good" agreement for 36T_B treatment with PBIAS and $R^2$ were -3.64% and 0.72 respectively. While the statistic results of 18T_A and 18T_B were "satisfactory" with PBIAS = 3.85% and 23.68% and $R^2$ = 0.56 and 0.69, respectively. In validation group, the model accuracy statistics for Fertilizer treatment was "good" (PBIAS = 8.36% and $R^2$ = 0.60) and for 52T_A and 52T_B treatments, they were "satisfactory" with |PBIAS| were between 15%-30% and $R^2$ > 0.40. The simulation result of Control treatment was unsatisfactory as $R^2$ = 0.38 as the model overestimated the barley uptake on P.

The analysis of crop yield presented similar results as well (Table 3-9). The RZWQM2-P model simulated the crop yield well matched with the observed values. For the Control treatment, the simulated results were "good" with PBIAS =13.93%. and for all other treatments, the statistical results were in "very good" agreements (PBIAS within ±10% and $R^2$ > 0.80). On average the PBIAS for our simulated sugar beet yield was -5.70% using the DSSAT sugar beet model, comparable to the PBIAS obtained when using the HERMES sugar beet model by Kohen et al (2021). Therefore, this minor difference suggests that both the DSSAT and HERMES model perform similarly in simulating the yield of sugar beet.

**Table 3-9. Simulated and observed plant uptake P (kg $ha^{-1}$) and crop yield (kg $ha^{-1}$) and their model accuracy statistics.**

| Plant P uptake | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Simulated | | | | | | | | | |
| Year | Crop | Calibration | | | | Validation | | | |
| | | 18T_A | 18T_B | 36T_A | 36T_B | 52T_A | 52T_B | Control | Fertilizer |
| 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 | | | | | | | | | |
| Year | Crop | Calibration | | | | Validation | | | |
| | | 18T_A | 18T_B | 36T_A | 36T_B | 52T_A | 52T_B | Control | Fertilizer |
| 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 | | | | | | | | | |
| Simulated | | | | | | | | | |
| Year | Crop | Calibration | | | | Validation | | | |
| | | 18T_A | 18T_B | 36T_A | 36T_B | 52T_A | 52T_B | Control | Fertilizer |
| 2014 | Potato | 10803 | 10734 | 10846 | 10793 | 10806 | 10808 | 8335 | 10428 |
| 2015 | Barley | 6961 | 9843 | 6245 | 6437 | 5827 | 6185 | 8477 | 8512 |
| 2016 | Sugar beet | 19447 | 20440 | 21136 | 19666 | 21133 | 19618 | 15692 | 20597 |
| Average | | 12404 | 13672 | 12742 | 12299 | 12589 | 12203 | 10835 | 13179 |
| Observed | | | | | | | | | |
| Year | Crop | Calibration | | | | Validation | | | |
| | | 18T_A | 18T_B | 36T_A | 36T_B | 52T_A | 52T_B | Control | Fertilizer |
| 2014 | Potato | 11683 | 11041 | 10998 | 11458 | 10137 | 11820 | 8473 | 11514 |
| 2015 | Barley | 6659 | 6506 | 6349 | 6429 | 6015 | 5601 | 4694 | 6690 |
| 2016 | Sugar beet | 21593 | 21945 | 22462 | 21956 | 22616 | 21230 | 15364 | 20085 |
| Average | | 13312 | 13164 | 13270 | 13281 | 12923 | 12884 | 9510 | 12763 |
| 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 |

### *3-3.4 Long term impacts of manure application on soil P recovery*

Illustrated in Figure 3-2a, the total $P_{lab}$ of the continuous treatment increased from the initial value of 241.30 kg $ha^{-1}$ to 2354.70 kg $ha^{-1}$ in the soil profile (0-154 cm) after 24 years of manure P application at a rate of roughly 347 kg $ha^{-1}$. It led to about 2.6 times higher $P_{lab}$ than recovery treatment (898.42 kg $ha^{-1}$) in which the same P rate was applied for the first 8 years but no P input for the rest 16 years. In the continuous treatment, labile P increased over the 24 years at a rate of 92.6 kg ha$^{-1}$ yr$^{-1}$; in the recovery treatment, $P_{lab}$start decreasing at a rate of 10.4 kg ha$^{-1}$ yr$^{-1}$ after the P input was terminated in the year of 16, as a result of annual average P removal by crop grain or tuber at 59.6 kg ha$^{-1}$ yr$^{-1}$, meanwhile the residue P entered soil organic P pools ($P_{inorg}^{stab}$ and $P_{org}^{stab}$) due to degradation and transfer from other P pools. At the end (year 24) the $P_{lab}$ decreased 15.68% from 2001 (year 8) when the application of P was discontinued in recovery treatment. The change of $P_{lab}$ mainly happened in the first soil layer (0-15 cm), therefore, the $P_{lab}$ amount in this soil layer of the continuous treatment presented a stable accumulation as years grow (Fig. 3-2), from 52.91 to 1339.20 kg ha$^{-1}$, while for recovery treatment, the $P_{lab}$ raised to 531.41 kg ha$^{-1}$ in the top soil layer after 8 years of P application at a rate same as the continuous treatment but decline to 24.96 kg ha$^{-1}$ because of no P added (Fig. 3-2) in the following 16 years, which was lower than initial soil labile P content. The $P_{lab}$ in the first soil layer took 14 years to go back to initial level. In the deeper soil layers (15-154 cm), the soil labile P maintained upward trends for both continuous and recovery treatments.

The control_lt scenario, with no manure and fertilizer input for continuous 24 years, showed that the total $P_{lab}$ in the whole soil profile decreased from the initial value of 101.00 kg ha$^{-1}$ to 69.18 kg ha$^{-1}$ at the end of year 24, then it fluctuated and finally stabilized in the range of 70-80 kg ha$^{-1}$(Fig. 3-3). Figure 3-3 depicts the liable P dynamics in each soil layer. In the top three soil layers (0-15, 15-30 and 30-60 cm), the amount of soil labile P presented alternating trends of rising and falling over time but overall decreased; the changes of the top two soil layers (0-15 and 15-30 cm) were more obvious as the plants absorbed P from surface soil layers firstly. While in the soil layers of 60-90 and 90-120 cm the soil labile P increased slightly and stayed almost constant for the deepest layer (120-154 cm) due to no P exchange activities occurred in deep soil layers. The simulated crop yield as affected by P stress indicated that the annual average crop yield decreased by 7.1%, 13.2% and 2.7% respectively for potato, barley and sugar beet when P stress happened in the control_lt scenario.

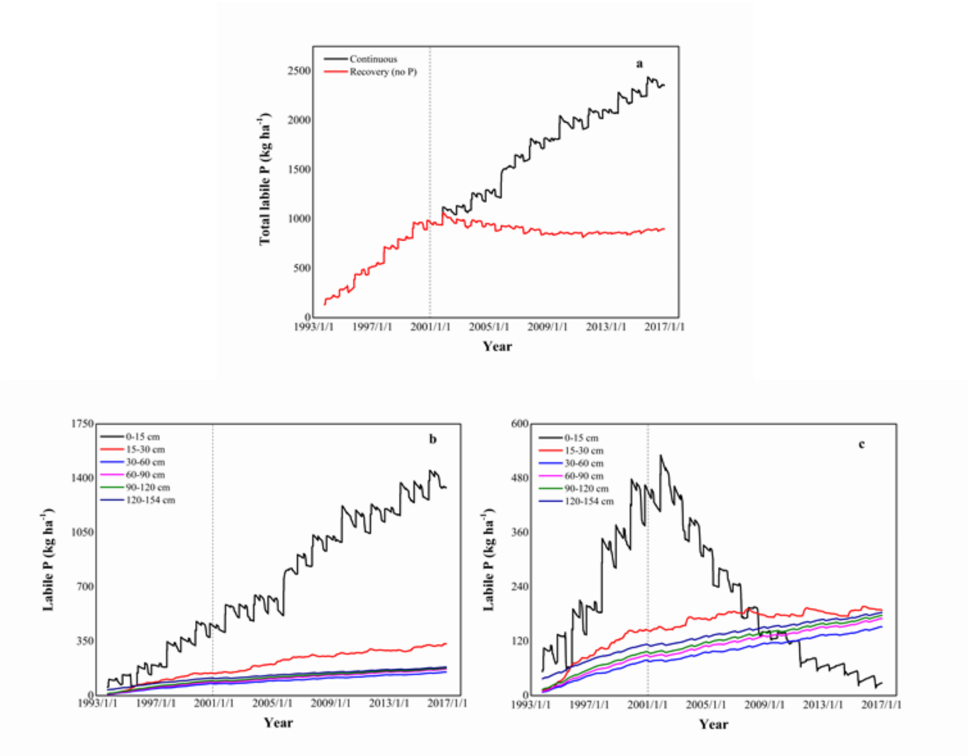



**Figure 3-2. Results of the 24-year simulations of total $P_{lab}$ change from all soil layers between continuous and recovery treatments (a) and $P_{lab}$ contents in soil profile in continuous treatment (b) and in recovery treatment (c).**

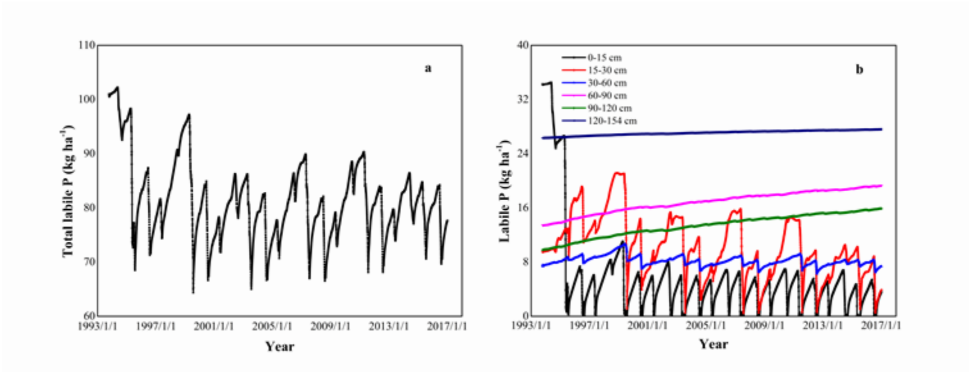



**Figure 3-3. Results of the 24-year simulations of total $P_{lab}$ in control_lt treatment from all soil layers (a) and $P_{lab}$ content in soil profile in control treatment (b).**

## 3-4. Discussion

Having been tested using observed soil and plant P data under various P application rates in an irrigated corn field in Idaho, USA, the RZWQM2-P model was found to perform well in predicting soil total P and plant uptake P in the potato-barley-sugar beet-wheat field amended with high manure application rates. To simulate total P is relatively easy as total P is in a large amount and varied little over years; however, fitting simulated $P_{lab}$ values, especially for different layers, with observed data was the most difficult part of this research. Although not all $P_{lab}$ fitted well with experimental data, the simulation results still can be considered satisfactory as the performance was acceptable for most of the treatments.

In this study, we found that it took a long time for the soil to recover $P_{lab}$ content to initial status for those plots being amended with high manure application rates. In the recovery treatment, the main $P_{lab}$ loss was through plant uptake, while the total $P_{upt}$ for 24 simulation years was 1449.41 kg ha$^{-1}$, only accounting for 47.47% of total input P (8 years manure 2552 kg ha$^{-1}$ and 24 years residue 501.10 kg ha$^{-1}$), and the total P loss through runoff was negligible, only account for 0.13%, and no P loss through deep seepage and subsurface drainage in this experimental site. All $P_{lab}$ loss activities occurred on surface soil layers, while the labile P increased in deep soil layers (30-154cm) was caused by P transfer between different P pools (Table 3-10). Figure 3-3 illustrated that the total $P_{lab}$ would not decrease to zero, fluctuating within a range in control_lt treatment. The fluctuating tendency of total $P_{lab}$ was the same as that of surface soil. The degradation of residue and organic matter was thought to be partly responsible for $P_{lab}$ rise in the soil, which resulted in part of $P_{upt}$ being returned to soil and transfer $P_{lab}$ from $P_{org}^{stab}$ and $P_{org}^{frsh}$. While the total $P_{lab}$ decrease was mainly caused by plant uptaking, meanwhile the desorption and immobilization in soil led $P_{lab}$ transfer to $P_{act}$ and $P_{org}^{frsh}$ (Fig. 3-4). The simulation results showed that the total input soil P from residue was 501.10 kg ha$^{-1}$ (21.79 kg P ha$^{-1}$ yr$^{-1}$) in the continuous treatment, which was 48.96% higher than that in the control_lt treatment (255.68 kg ha$^{-1}$). In the control_lt treatment, there was almost no increase in $P_{lab}$ in soil layer below 120 cm (Fig. 3-3), while $P_{lab}$ presented a rising trend in the continuous treatment. This may be caused by higher ratio between $P_{inorg}^{stab}$ and $P_{act}$, leading to more $P_{act}$ move to $P_{inorg}^{stab}$ pool through slow absorption and less P from $P_{act}$

transfer to $P_{lab}$ pool.

**Table 3-10. The P content changes in separate layers from different P pools during the 24-year simulation period and their balance**

| Soil depth | $P_{lab}$ | $P_{act}$ | $P_{inorg}^{stab}$ | $P_{org}^{stab}$ | $P_{org}^{frsh}$ | Balance |
|---|---|---|---|---|---|---|
| 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 |
| | | | Recover | | | |
| 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 |

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 pools changes.

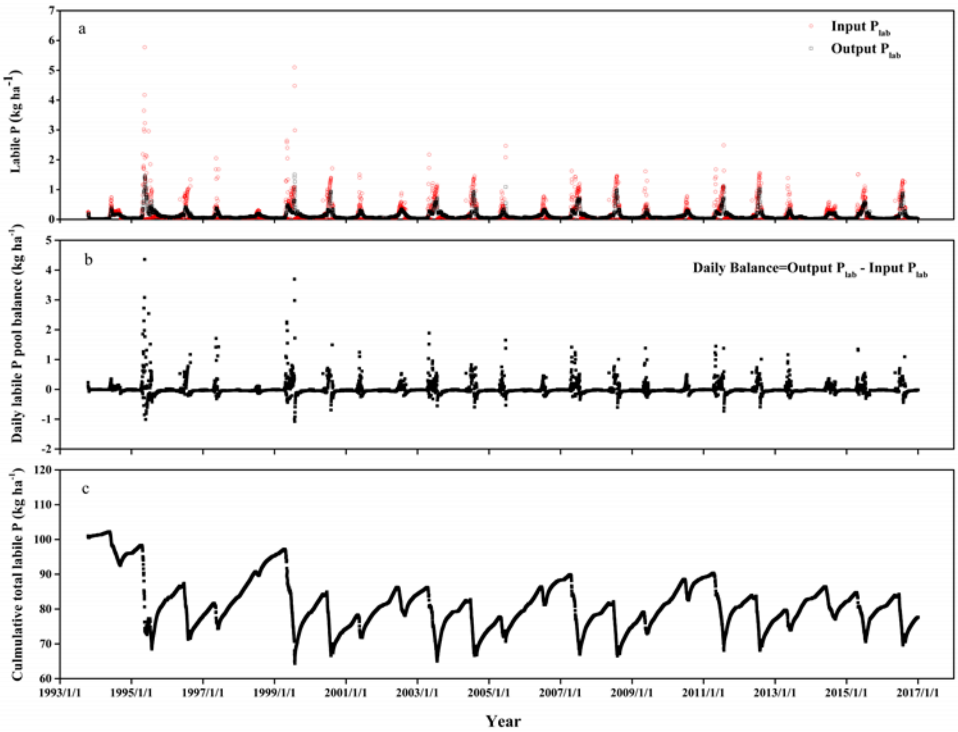



**Figure 3-4. Long-term simulation results of input and output P in labile P pool (a), daily labile P pool**

**change (b) and cumulative labile P (c) from all soil layers in control_lt treatment**

## 3-5. Conclusions

The impact of high manure P amendment on $P_{tot}$ and $P_{lab}$, $P_{upt}$ and crop yield were simulated using the modified RZWQM2-P model for an irrigated dryland corn field in Idaho. The simulation results showed that the RZWQM2-P model performed well in predicting $P_{tot}$ and $P_{lab}$ compared with experimental data, though less accurate simulated $P_{lab}$, it was considered acceptable as it worked well in most of the treatments. The long-term simulation indicated that the $P_{lab}$ in surface soil layer is able to recover to the initial level 14 years after manure P application was terminated. For deeper soil layers (60 cm – 154 cm), the supplement from other P pools resulted in an increasing tendency of $P_{lab}$. The main consumption activities, such as runoff P loss and plant P uptake, of soil labile P occurred in surface soil layers. Therefore, applying the proper amount of P on farm field can reduce the waste of P and risk of P pollution. In this crop rotation case, about 120 kg P $ha^{-1}$ $yr^{-1}$ would be enough for crop growth and insufficient for soil P accumulation. In the future, we hope to improve the accuracy and reasonability of soil P dynamics in RZWQM2-P model, such as improving P activities between adjacent soil layers and expanding P added depth from manure, and soil P content simulation still needs to be further tested using more datasets.

## Appendix

**Table3-A1. Observed and simulated total P amount in soil profile in the year of 2014 and 2017**

| Depth | 10_A | | 10_B | | 20_A | | 20_B | | 30_A | | 30_B | | Control | | Fertilizer | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. |
| cm | kg ha$^{-1}$ | | | | | | | | | | | | | | | |
| 2014 | | | | | | | | | | | | | | | | |
| 15 | 1433 | 2351 | 1458 | 1605 | 1488 | 1585 | 1481 | 1771 | 1610 | 1876 | 1509 | 1984 | 1400 | 1383 | 1391 | 1528 |
| 30 | 1539 | 1925 | 1572 | 1435 | 1654 | 1422 | 1529 | 1443 | 1785 | 1471 | 1602 | 1487 | 1556 | 1418 | 1561 | 1463 |
| 60 | 2785 | 2615 | 2795 | 2705 | 3088 | 2787 | 2935 | 2678 | 2888 | 2401 | 2984 | 2606 | 2818 | 2482 | 2765 | 2536 |
| 90 | 2876 | 3041 | 3030 | 2818 | 2951 | 2896 | 2928 | 2893 | 3042 | 2783 | 2936 | 2795 | 3036 | 2831 | 2912 | 2934 |
| 122 | 3273 | 3622 | 3222 | 3082 | 3138 | 3121 | 3147 | 3080 | 3263 | 2957 | 3249 | 3102 | 3283 | 2980 | 3115 | 3190 |
| Average | 2381 | 2711 | 2415 | 2329 | 2464 | 2362 | 2404 | 2373 | 2517 | 2298 | 2456 | 2395 | 2418 | 2219 | 2349 | 2330 |
| PBIAS | 13.84% | | -3.59% | | -4.12% | | -1.29% | | -8.72% | | -2.49% | | -8.26% | | -0.79% | |
| R2 | 0.79 | | 0.98 | | 0.96 | | 0.95 | | 0.88 | | 0.88 | | 0.99 | | 0.97 | |
| 2017 | | | | | | | | | | | | | | | | |
| 15 | 1918 | 2393 | 1852 | 1530 | 2157 | 1859 | 1840 | 1795 | 2446 | 2299 | 1953 | 2234 | 1588 | 1272 | 1711 | 1371 |
| 30 | 1742 | 2040 | 1831 | 1519 | 1985 | 1552 | 1703 | 1534 | 2257 | 1652 | 1856 | 1562 | 1840 | 1440 | 1677 | 1527 |
| 60 | 2847 | 2615 | 3220 | 2705 | 3111 | 2787 | 3047 | 2678 | 3031 | 2401 | 2883 | 2606 | 2984 | 2478 | 3023 | 2536 |
| 90 | 3129 | 3041 | 3314 | 2818 | 3194 | 2896 | 3053 | 2893 | 3091 | 2783 | 3134 | 2795 | 3155 | 2830 | 3118 | 2934 |
| 122 | 3442 | 3622 | 3426 | 3082 | 3553 | 3121 | 3338 | 3080 | 3443 | 2957 | 3539 | 3102 | 3456 | 2980 | 3410 | 3190 |
| Average | 2616 | 2742 | 2729 | 2331 | 2800 | 2443 | 2596 | 2396 | 2853 | 2418 | 2673 | 2460 | 2605 | 2200 | 2588 | 2312 |
| PBIAS | 4.83% | | -14.59% | | -12.74% | | -7.71% | | -15.24% | | -7.97% | | -15.54% | | -10.68% | |
| R2 | 0.87 | | 0.99 | | 0.99 | | 0.98 | | 0.84 | | 0.87 | | 0.99 | | 0.97 | |

**Table 3-A2. Observed and simulated labile P amount in soil profile in the year of 2014, 2015, 2016 and 2017**

| 2014 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Depth | 10_A | 10_B | 20_A | 20_B | 30_A | 30_B | Control | Fertilizer |

| | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| cm | kg ha | | | | | | | | | | | | | | | |
| 15 | 66.02 | 57.44 | 42.87 | 90.18 | 88.35 | 98.47 | 62.13 | 95.16 | 148.98 | 197.28 | 61.56 | 108.49 | 26.37 | 22.74 | 33.64 | 60.79 |
| 30 | 26.18 | 29.70 | 9.39 | 21.43 | 27.40 | 24.22 | 19.02 | 16.38 | 48.90 | 33.48 | 21.21 | 18.19 | 10.25 | 15.05 | 13.20 | 17.61 |
| 60 | 10.72 | 19.35 | 15.46 | 8.64 | 7.57 | 10.43 | 11.81 | 9.75 | 30.44 | 8.38 | 15.63 | 9.37 | 7.82 | 7.75 | 9.58 | 6.43 |
| 90 | 22.64 | 23.29 | 18.05 | 9.58 | 14.73 | 35.00 | 22.70 | 15.04 | 27.29 | 7.61 | 14.38 | 14.84 | 8.55 | 13.85 | 17.26 | 10.82 |
| 122 | 18.78 | 28.71 | 16.43 | 11.32 | 22.07 | 24.27 | 21.87 | 18.53 | 27.06 | 12.05 | 23.42 | 14.73 | 11.60 | 10.28 | 18.57 | 13.88 |
| Average | 28.87 | 31.70 | 20.44 | 28.23 | 32.02 | 38.48 | 27.51 | 30.97 | 56.53 | 51.76 | 27.24 | 33.12 | 12.92 | 13.94 | 18.45 | 21.91 |
| PBIAS | 9.80% | | 38.11% | | 20.16% | | 12.60% | | -8.44% | | 21.61% | | 7.89% | | 18.73% | |
| R2 | 0.96 | | 0.85 | | 0.93 | | 0.98 | | 1.00 | | 0.97 | | 0.76 | | 0.88 | |
| 2015 | | | | | | | | | | | | | | | | |
| 15 | 105.29 | 45.64 | 75.02 | 55.36 | 142.35 | 98.07 | 105.62 | 87.70 | 225.86 | 233.24 | 258.44 | 125.31 | 20.49 | 3.15 | 33.35 | 25.51 |
| 30 | 49.72 | 54.48 | 33.14 | 39.37 | 89.76 | 44.40 | 51.31 | 32.64 | 125.67 | 55.03 | 113.82 | 32.05 | 13.30 | 19.94 | 15.56 | 30.95 |
| 60 | 10.80 | 32.27 | 7.71 | 9.48 | 27.58 | 11.39 | 9.88 | 10.67 | 61.06 | 9.36 | 21.21 | 10.29 | 6.99 | 8.05 | 6.13 | 7.46 |
| 90 | 6.15 | 37.86 | 4.16 | 10.12 | 5.44 | 35.58 | 3.90 | 15.61 | 7.51 | 8.17 | 5.09 | 15.41 | 5.32 | 14.40 | 6.35 | 11.37 |
| 122 | 7.50 | 43.97 | 5.58 | 11.83 | 5.13 | 24.80 | 3.99 | 19.05 | 5.11 | 12.57 | 4.53 | 15.26 | 4.55 | 10.80 | 6.06 | 14.39 |
| Average | 35.89 | 42.84 | 25.12 | 25.23 | 54.05 | 42.85 | 34.94 | 33.13 | 85.04 | 63.68 | 80.62 | 39.67 | 10.13 | 11.27 | 13.49 | 17.93 |
| PBIAS | 19.36% | | 0.44% | | -20.72% | | -5.16% | | -25.12% | | -50.80% | | 11.24% | | 32.94% | |
| R2 | 0.26 | | 0.94 | | 0.76 | | 0.93 | | 0.85 | | 0.92 | | 0.12 | | 0.49 | |
| 2016 | | | | | | | | | | | | | | | | |
| 15 | 64.39 | 58.51 | 42.80 | 40.06 | 163.07 | 128.37 | 75.44 | 81.09 | 293.09 | 327.30 | 120.17 | 109.64 | 20.10 | 3.07 | 30.11 | 9.15 |
| 30 | 27.89 | 75.87 | 20.12 | 41.71 | 93.09 | 64.36 | 26.11 | 35.32 | 126.31 | 78.82 | 66.57 | 34.25 | 9.15 | 10.36 | 13.62 | 30.28 |
| 60 | 8.41 | 44.86 | 7.62 | 10.27 | 28.46 | 12.17 | 8.05 | 11.48 | 31.45 | 10.15 | 11.19 | 11.10 | 6.27 | 7.53 | 6.13 | 8.30 |
| 90 | 6.38 | 50.45 | 5.55 | 10.60 | 10.11 | 36.06 | 6.84 | 16.09 | 10.61 | 8.64 | 6.15 | 15.89 | 5.98 | 14.79 | 7.20 | 11.85 |
| 122 | 4.98 | 56.29 | 9.49 | 12.26 | 10.45 | 25.23 | 6.13 | 19.48 | 8.32 | 13.00 | 9.40 | 15.68 | 6.33 | 11.22 | 14.48 | 14.82 |
| Average | 22.41 | 57.20 | 17.12 | 22.98 | 61.04 | 53.24 | 24.52 | 32.69 | 93.96 | 87.58 | 42.70 | 37.31 | 9.57 | 9.40 | 14.31 | 14.88 |
| PBIAS | 155.25% | | 34.24% | | -12.77% | | 33.36% | | -6.79% | | -12.61% | | -1.79% | | 4.00% | |
| R2 | 0.15 | | 0.69 | | 0.90 | | 0.98 | | 0.96 | | 0.90 | | 0.66 | | 0.01 | |
| 2017 | | | | | | | | | | | | | | | | |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15 | 101.23 | 65.04 | 70.72 | 55.85 | 180.80 | 170.41 | 96.24 | 110.08 | 268.02 | 379.01 | 246.41 | 202.73 | 19.05 | 4.06 | 44.69 | 5.32 |
| 30 | 49.71 | 93.92 | 29.71 | 56.99 | 131.97 | 87.40 | 44.67 | 56.06 | 201.45 | 114.47 | 90.13 | 50.07 | 13.67 | 15.16 | 15.51 | 36.27 |
| 60 | 14.23 | 50.82 | 11.79 | 10.54 | 34.55 | 12.43 | 15.05 | 11.72 | 40.23 | 10.36 | 20.94 | 11.35 | 10.63 | 8.26 | 9.34 | 8.45 |
| 90 | 10.49 | 58.21 | 10.30 | 10.89 | 9.99 | 36.36 | 9.47 | 16.38 | 11.97 | 8.91 | 10.78 | 16.18 | 10.56 | 15.11 | 10.84 | 12.13 |
| 122 | 22.31 | 64.48 | 10.93 | 12.55 | 9.46 | 25.52 | 9.12 | 19.77 | 11.05 | 13.28 | 11.12 | 15.97 | 11.57 | 11.52 | 12.54 | 15.10 |
| Average | 39.59 | 66.49 | 26.69 | 29.36 | 73.35 | 66.42 | 34.91 | 42.80 | 106.54 | 105.21 | 75.88 | 59.26 | 13.10 | 10.82 | 18.58 | 15.45 |
| PBIAS | 67.95% | | 10.02% | | -9.44% | | 22.61% | | -1.26% | | -21.90% | | -17.37% | | -16.83% | |
| R2 | 0.12 | | 0.67 | | 0.88 | | 0.98 | | 0.82 | | 0.98 | | 0.41 | | 0.11 | |

# CHAPTER 4 SUMMARY AND CONCLUSION

This study aims to evaluate and enhance newly-developed RZWQM2-P model performance on predicting P loss through drainage and soil P content in two manure amended croplands, and investigate the influence of management practices on soil P losses and transfer, and provide meaningful guidance on mitigating P losses and waste from agricultural field. In chapter 2, the RZWQM2-P model was evaluated in predicting DRP, PP and TP loss through subsurface drainage against experimental data collected in Harrow experimental site Ontario, and the model accuracy statistics results demonstrated that the model accurately predicted field-measured PP and TP loss in drainage, while underestimated DRP loss in drainage when compost applied, which may because the decomposition rate of P manure is too fast in model. Then the model application results presented that the tillage parameters TI/ME was negatively correlated to drainage water flow and DRP and PP loss through drainage. The changes of soil bulk density, evaporation and residue mass caused by different intensive tillage practices were responsible for the subsurface drainage change, and meanwhile the incorporation of compost and the destruction of soil macropores by tillage affected the P content entering groundwater as well. Ultimately, the mix efficiency was added in RZWQM2-P model and the unreasonable relationship between TI and ME was fixed.

In chapter 3, soil $P_{lab}$ and $P_{tot}$ content in soil profile, plant P uptake and crop yield were simulated using the RZWQM2-P model to match the observed values collected in Idaho. The model performances were satisfactory according to accuracy statistics results. The long-term simulation indicated that it took a long time for surface soil to recover $P_{lab}$ content to initial status after manure amendment, while the $P_{lab}$ in deep layers showed a slow increase due to P transfer between $P_{lab}$ and other P pools. In this simulation, the insufficiencies of the P model on simulating soil P dynamics appeared and were corrected accordingly. The transfer ratio between $P_{act}$ and $P_{inorg}^{stab}$ was adjusted to dynamic instead of a fixed value; the transfer flow between $P_{org}^{stab}$ and $P_{act}$ was ceased due to lack of reference supporting; the P stress was determined by the ratio between actual and optimum plant P biomass.

Overall, the modified model was mainly used to simulate P losses and soil P content and match the observed data in this thesis. P stress function in RZWQM2-P model can affect crop yield under insufficient P condition, however its prediction accuracy has not been verified due to lack of experimental data to compare. Therefore, investigation in simulating P content and transfer in soil profile and yield change under P stress are recommended in future studies to enhance model prediction performance.

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