Science of the Total Environment 639 (2018) 580–587

Contents lists available at ScienceDirect

Science of the Total Environment

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

Modeling phosphorus losses from soils amended with cattle manures and chemical fertilizers

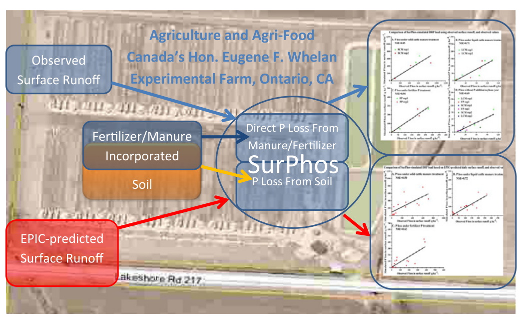
Zhaozhi Wang [a], T.Q. Zhang [a,*], C.S. Tan [a], P. Vadas [b], Z.M. Qi [c], C. Wellen [d]

[a] Harrow Research and Development Centre, Agriculture & Agri-Food Canada, Harrow, ON, N0R 1G0, Canada
[b] USDA-ARS, U.S. Dairy Forage Research Center, 1925, Linden DriveWest, Madison, WI 53706, United States
[c] Department of Bioresource Engineering, McGill University, Sainte-Anne-de-Bellevue, QC H9X 3V9, Canada
[d] Department of Geography and Environmental Studies, Ryerson University, Toronto, ON, Canada

HIGHLIGHTS

- SurPhos showed reliable prediction of DRP loss with observed surface runoff.
- SurPhos showed satisfactory results with EPIC-predicted daily surface runoff.
- SurPhos is able to simulate soil P dynamics under different P management practices.
- SurPhos can quantify different sources (soil, manure/fertilizer) of DRP loss.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 23 March 2018
Received in revised form 27 April 2018
Accepted 11 May 2018
Available online 26 May 2018

Editor: Ouyang Wei

Keywords:
Dissolved reactive phosphorus (DRP)
Modeling
Manure
Fertilizer
SurPhos
EPIC

ABSTRACT

While applied manure/fertilizer is an important source of P loss in surface runoff, few models simulate the direct transfer of phosphorus (P) from soil-surface-applied manure/fertilizer to surface runoff. The SurPhos model was tested with 2008–2010 growing season daily surface runoff data from clay loam experimental plots subject to different manure/fertilizer applications. Model performance was evaluated on the basis of the coefficient of determination (R^2), Nash-Sutcliffe efficiency (*NSE*), percent bias (*PBIAS*), and the ratio of the root mean square error to the standard deviation of observed values (*RSR*). The model offered an acceptable performance in simulating soil labile P dynamics ($R^2 = 0.75$, $NSE = 0.55$, $PBIAS = 10.43\%$, and $RSR = 0.67$) and dissolved reactive P (DRP) loss in surface runoff ($R^2 \geq 0.74$ and $NSE \geq 0.69$) for both solid and liquid cattle manure, as well as inorganic fertilizer. Simulated direct P loss in surface runoff from solid and liquid cattle manure accounted for 39% and 40% of total growing season DRP losses in surface runoff. To compensate for the unavailability of daily surface runoff observations under snow melt condition, the whole four years' (2008–2011) daily surface runoff predicted by EPIC (Environmental Policy Integrated Climate) was used as SurPhos input. The accuracy of simulated DRP loss in surface runoff under the different manure/fertilizer treatments was acceptable ($R^2 \geq 0.55$ and $NSE \geq 0.50$). For the solid cattle manure treatment, of all annual DRP losses, 19% were derived directly from the manure. Beyond offering a reliable prediction of manure/fertilizer P loss in surface runoff, SurPhos quantified different sources of DRP loss and dynamic labile P in soil, allowing a better critical assessment of different P management measures' effectiveness in mitigating DRP losses.

* Corresponding author.
E-mail address: Tiequan.Zhang@agr.gc.ca (T.Q. Zhang).

https://doi.org/10.1016/j.scitotenv.2018.05.141
0048-9697/

1. Introduction

Non-point source phosphorus (P) losses from agricultural lands that accelerate eutrophication in receiving water bodies (Bennett et al., 2001; Sharpley et al., 2015) and potentially lead to toxic cyanobacterial blooms such as those observed in the western basin of Lake Erie in 2011 (Daloglu et al., 2012; Michalak et al., 2013), constitute a serious water quality concern. While there are three main contributors to dissolved P in surface runoff: crop residue, soil, and applied manure/fertilizer (Collick et al., 2016), the latter can contribute a majority, especially soon after its application (Kleinman et al., 2002; Withers et al., 2001). Since manure/fertilizer can account for the majority of annual dissolved P losses (Owens and Shipitalo, 2006), it is critical to understand how alternative manure/fertilizer management practices might contribute to reducing such losses. When such applications exceed crop needs, soil P may rise over time and from season to season contribute to the pool of so-called legacy P (Sharpley et al., 2013). Accordingly, to rank alternative management practices' relative ability to reduce overall soil P, it is important to assess how P applications affect quantity and distribution of soil P's different chemical forms.

The quantity of surface-applied manure P lost in runoff is closely tied to the timing of manure/fertilizer application relative to precipitation/runoff events, precipitation intensity, and the quantity and forms of P in the manure/fertilizer (Edwards and Daniel, 1993; Kleinman et al., 2007). Based on first- and second-order P desorption kinetics, Gerard-Marchant et al. (2005) derived two simple equations to predict water-extractable P release from animal manure during a rainfall event. In exploring a method to estimate P source coefficients in the context of the P index, Elliott et al. (2006) correlated runoff dissolved P with water-extractable P for multiple surface-applied manures and biosolids. Soil P forms and content also influence dissolved P loss in runoff. For example, Wang et al. (2015) found significant relationships between soil test P levels of 391 topsoil samples collected across Ontario and P loss potential. Although there exists an abundance of empirical observations and mathematical relationships to quantify dissolved P loss in runoff, few of these have been incorporated into models or been widely tested (Radcliffe et al., 2015).

Less time-consuming and costly than field experiments, computer models, commonly used to predict soil P dynamics for scientific, management, and policy evaluation purposes, offer the opportunity to improve our scientific understanding of these processes (Garcia et al., 2008). However, such models must be stringently developed and appropriately applied to reliably represent soil and runoff P dynamics. Employed in many existing models [e.g., APEX (Agricultural Policy/Environmental eXtender) (Gassman et al., 2010), EPIC (Environmental Policy Integrated Climate) (Peruta et al., 2014), ICECREAM (Rekolainen and Posch, 1993; Tattari et al., 2001), SWAT (Soil and Water Assessment Tool) (Collick et al., 2016)], the soil P subroutines developed by Jones et al. (1984) assume that applied manure/fertilizer is well mixed into soil and its P quickly incorporated into the soil's P pool; it does not consider P losses directly from manure/fertilizer to runoff. Accordingly, models based on this premise may offer poor simulations for a situation such as a large or intense precipitation event shortly after manure/fertilizer application, when manure or fertilizers on the soil surface represent significant sources of dissolved P loss in surface runoff (Collick et al., 2016; Vadas et al., 2017).

Accordingly, to address direct loss of P from manure or fertilizer on the soil surface, Vadas et al. (2007) developed and tested the SurPhos model, with the aim of incorporating the model into a more complete, process-based model such as EPIC or SWAT. Implementing other advances to better simulate soil P dynamics (Vadas et al., 2006), SurPhos can estimate the dynamic fate of applied manure/fertilizer P, i.e. quantify the different sources of P lost in surface runoff. SurPhos has been incorporated into the Integrated Farming Systems Model (IFSM) (Sedorovich et al., 2007) and SWAT (Collick et al., 2016), and compared with SWAT alone (Sen et al., 2012).

The SurPhos model also served as the basis for the development of the Annual P Loss Estimator (APLE), which was tested for P loss prediction in surface runoff (Vadas et al., 2012). By incorporating estimates of P loss from APLE into the Chesapeake Bay watershed model (WSM), Mulkey et al. (2017) improved WSM's performance. Fiorellino et al. (2017) used the estimated P loss data from APLE to evaluate the Maryland P Site Index. While these successful applications of SurPhos support its capacity and advantages for P loss prediction in surface runoff, the model requires evaluation over a wider range of field-scale situations (e.g., different soil and manure/fertilizer types).

For the site under study, snowmelt significantly influenced surface runoff during the non-growing season, such that observed surface runoff exceeded precipitation on some days (Tan and Zhang, 2011). The SurPhos model requires daily precipitation and surface runoff as inputs, which could present a problem when such measured data are unavailable. Alternatively, the EPIC model contains an improved snowmelt runoff component (Williams et al., 2015) and offers robust daily surface runoff prediction using the modified Natural Resources Conservation Service (NRCS) curve number with soil moisture index (Wang et al., 2018). Thus, we aim to: 1) test the SurPhos model's abilities to predict field scale P losses in surface runoff arising under natural rainfall conditions, from soils having received different types of organic (solid or liquid cattle manure) or inorganic fertilizer applications over multiple cropping seasons drawing on observed (Lake Erie region) surface runoff volume; 2) test one alternative method to use the predicted daily snowmelt and surface runoff from EPIC as SurPhos input when these data were unavailable.

2. Methods and materials

2.1. Field experiments

Data for model simulation testing were drawn from field experiments conducted on plots at Agriculture and Agri-Food Canada's Hon. Eugene F. Whelan Experimental Farm at Woodslee, ON. The soil is a Brookston clay loam, with 36% clay, 40% silt, and 24% sand; which was classified as an Orthic Humic Gleysol (Soil Classification Working Group, 1998). The soil's bulk density (ρ) was 1.33 Mg m^3, while its volumetric (m^{-3} m^{-3}) field capacity and permanent wilting points (θ_{fc} and θ_{pwp}) were 0.38 and 0.18, respectively. Data employed for model validation were gathered from six plots with different P fertilizer/manure management practices (Table 1), each replicated twice. The cropping system was a corn-soybean rotation. In 2008, corn (*Zea mays* L.) was planted on June 18, at a density of 79,800 seeds ha^{-1}, and then harvested on November 5; while in 2010, it was planted on 26 June at a density of 79,700 seeds ha^{-1}, and then harvested on November 8. In 2009, soybean [*Glycine* max (L.) Merr.] was planted on May 22 at a density of 486,700 seeds ha^{-1}, and then harvested on October 20. The

Table 1
Field experimental details under manure/fertilizer treatments.

	Treatment	Solid cattle manure	Liquid cattle manure	Fertilizer P
2008	Wet mass (kg ha^{-1})	53,001	273,635	
	P_{tot} (%)[a]	0.094	0.018	
	P rate (kg ha^{-1})	50	50	50
	Dry Matter (%)	25	4.3	
	Application date	JUN 2 and 3	JUN 2, 6, and 9	JUN 2
	Tillage	JUN 3, NOV 18	JUN 17, NOV 18	JUN 3, NOV 18
2010	Wet mass (kg ha^{-1})	28,115	338,551	
	P_{tot} (%)	0.18	0.015	
	P rate (kg ha^{-1})	50	50	50
	Dry Matter (%)	27	1.0	
	Application date	JUN 11	JUN 12, 13, 17, 25	JUN 25
	Tillage	JUN 11, NOV 19	JUN 25, NOV 19	JUN 25, NOV 19

[a] P_{tot}, total P.