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Simulating crop yield, surface runoff, tile drainage and phosphorus loss in a clay loam soil of the Lake Erie region using EPIC

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ABSTRACT

Useful in evaluating best management practices and nutrient management planning, the prediction of phosphorus (P) transfer from agricultural lands to water bodies via surface runoff and tile drainage remains as a challenge, as few models can provide reasonably accurate P loss simulations. The EPIC (Environmental Policy Integrated Climate) model was firstly applied to simulate crop yields, surface runoff, tile drainage, and dissolved reactive P (DRP) losses under a corn-soybean rotation grown on a "cracking" Brookston clay loam soil (Vertisol) in the Lake Erie basin, Ontario, Canada. Different potential evapotranspiration and curve number equations were compared to determine the most suitable equations (Penman-Monteith equation and variable Daily Curve Number with soil moisture index) for this region. A crack flow coefficient was used to deal with inflow partitioned to cracks. A soil layer below tile drain with low saturated hydraulic conductivity was employed in simulating the experimental site, where most water was leaving the field through tile drain. Lateral subsurface flow was used to substitute for drainage. Annual simulations of crop grain yield, cumulative surface runoff, and cumulative drainage closely matched observed data. Over shorter periods (months), surface runoff (NSE = 0.78), tile drainage (NSE = 0.57), and relevant DRP loss (NSE > 0.5) simulations were satisfactory, except for two periods of DRP loss in surface runoff, where most DRP moved downward through lateral flow and deep percolation due to limitations in the crack flow coefficient. For this vertic soil, EPIC generally simulated crop yields and flow volumes well, while DRP losses were only adequately simulated.

1. Introduction

Estimates based on simulations using SWAT (Soil and Water Assessment Tool) (Neitsch et al., 2011) suggest that Lake Erie's worst and most harmful cyanobacteria bloom, which occurred in 2011, was mainly attributable to long term dissolved reactive phosphorus (DRP) loss from agricultural lands (Daloglu et al., 2012; Michalak et al., 2013). Several studies have shown that both surface runoff and tile drainage are important pathways for P discharge from agricultural lands (Smith et al., 2015; Tan and Zhang, 2011; Zhang et al., 2015a). Accurate prediction of non-point source P loss and appropriate recommendations to support total P reduction targets announced by the Canada-US Great Lakes Water Quality Agreement (GLWQA) and the Canada-Ontario Agreement on Great Lakes Water Quality and Ecosystem Health (COA) are extremely urgent (Water Quality in Ontario 2014 Report).

Southern Ontario is dominated by high-nutrient-demand crops, with arable lands presenting a high risk of surface runoff and tile drainage bearing nutrients (*e.g.*, N and P) into the Lake Erie basin (Tan and Zhang, 2011). Characterized by shrinkage cracks (Reynolds et al., 2002), the "cracking" Brookston clay loam soil (Vertisol) at the experimental site is prone to preferential flow via cracks, as well as earthworm and root channels. Preferential flow that funnels water from surface to tile drainage is typical in this region, especially after a heavy precipitation event (Tan and Zhang, 2011; Zhang et al., 2015a; Zhang et al., 2015b). To accurately predict surface runoff, tile drainage and relevant nutrient loss in the regions dominated by soils exhibiting vertic properties, temporal changes in soil crack volume and infiltration must be quantified (Neitsch et al., 2011).

Recent P loss model improvements and model applications include: (i) the separation of organic (manure) and inorganic (fertilizer) P pools (Vadas et al., 2007), (ii) the implementation of variable source areas (Ghebremichael et al., 2010), (iii) the ability to undertake sensitivity and uncertainty analyses (Peruta et al., 2014), and (iv) the ability to complete economic analyses of BMPs (Beneficial Management Practices) (Rao et al., 2012). However, these models still deal poorly with P

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sorption/desorption processes (Rossi et al., 2012), as well as spatial (field to watershed) and temporal (daily to annual) scales issues (Radcliffe et al., 2009). According to a recent review (Radcliffe et al., 2015), eight models had been reviewed for simulation of P loss in drainage waters, including ADAPT (Agricultural Drainage and Pesticide Transport), APEX (Agricultural Policy/Environmental eXtender), DRAINMOD, HSPF (Hydrologic Simulation Program–Fortran), HYDRUS, ICECREAMDB, PLEASE (Phosphorus LEAching from Soils to the Environment), and SWAT. They found the ICECREAMDB model has macropore and P components; however, neither the overall model, nor its new approach to partitioning surface runoff and macropore flow, according to the complex and uncertain interaction of surface runoff and drainage, has been tested. Several widely-used models lack P submodels (*e.g.*, RZWQM2 (Root Zone Water Quality Model) and DRAINMOD). Others (*e.g.* EPIC, APEX and SWAT) are spatially explicit hydrologic models capable of predicting P losses that lack experimental corroboration to confirm the quality of their performance in modelling P loss. Accordingly, we sought to evaluate the performance of the field scale model-EPIC for DRP loss.

EPIC incorporates the popular P model of Jones et al. (1984) and is capable of simulating P losses in surface runoff (Peruta et al., 2014; Vadas et al., 2006). However, EPIC has not been tested with a vertisol due to its limitations in simulating nutrient transport through tile drainage (Wang et al., 2012). Previously, EPIC has been incorporated with a drainage system component similar to DRAINMOD (Sabbagh et al., 1991a; Sabbagh et al., 1993), but it was not tested because of its complexity. The current version of the model simplifies drainage volume by modifying the lateral subsurface flow of the area, where depth of the drainage system and the time required for the drainage system to reduce plant stress are used for adjustment (Williams et al., 2015). Adjusting these parameters could be useful in improving the accuracy of surface runoff predictions; however, for the vertic clay loam soil under study, the prediction of surface runoff would be unreliable without concurrently considering preferential flow. Since EPIC does not include preferential flow or macropore flow procedures (Radcliffe et al., 2015), we used the crack flow coefficient PARM(17) to deal with inflow partitioned to cracks or pipe flow. Baffaut et al. (2015) set the crack flow coefficient equal to 0.5 in their SWAT simulation of the Goodwater Creek Experimental Watershed. EPIC (field scale), APEX (whole farm and small watershed) and SWAT (large river basin) have the same P routine, facilitating scale-up. All three models are open source, permitting users to modify the code for their own investigations.

As EPIC has not been tested under the typical “cracking” Brookston clay loam soil of the Lake Erie region, our objectives were to: (i) compare the impacts of different potential evapotranspiration (ET_p) and curve number (CN) equations on crop yields, surface runoff, drainage and P losses, and thereby select the most suitable ET_p and CN equations through model calibration; (ii) evaluate EPIC’s ability to predict crop yield, surface runoff, drainage and soil P losses under a corn-soybean rotation in a clay loam soil (vertisol); and iii) specify the EPIC model’s limitations in terms of simulating surface runoff, drainage and relevant P loss.

2. Material & methods

2.1. Field experiments

Field experiments conducted from 2008 to 2011 on the Hon. Eugene F. Whelan Research Farm of the Harrow Research and Development Centre, Agriculture and Agri-Food Canada at Woodslee, ON were used as the basis for modelling agricultural runoff in the Brookstone Vertisol. Brookston is a clay loam, with 36.3% clay, 39.7% silt, and 23.9% sand. Permanent wilting point (θ_{pwp}) and field capacity (θ_{fc}) at the experimental site were 18.3% and 37.9% H_2O, respectively; bulk density, ρ, was 1.33 Mg m^{-3}.

The plot was 67.1 m long and 15.2 m wide; approximately 0.1 ha. The cropping system was a corn-soybean rotation. Corn (*Zea mays* L.) was planted at a density of 79,800 seeds ha^{-1} on June 18, and harvested on November 5, 2008; while in 2010, it was planted at a density at 79,700 seeds ha^{-1} on June 26, and harvested on November 8. Soybean [*Glycine max* (L.) Merr.] was planted at 486,700 seeds ha^{-1} on May 22, and harvested on October 20, 2009. In 2011, soybean was planted at the same seeding rate on June 15, and harvested on December 13. Prior to planting, the corn crops were fertilized with 200 kg N ha^{-1} of ammonium nitrate and 100 kg K ha^{-1} as KCl. No P fertilizer was applied during the experiment (2008–2011), based on the soil testing recommendations (OMAFRA, 2009). Herbicides were applied to corn – 1.4 kg ha^{-1} of Roundup [N-(phosphonomethyl)glycine], 1.4 kg ha^{-1} of Dual II [80% (a*RS*,1*S*)-2-chloro-6′-ethyl-*N*-(2-methoxy-1-methylethyl)acet-o-toluidide and 20% (a*RS*,1*R*)-2-chloro-6′-ethyl-*N*-(2-methoxy-1-methylethyl)acet-o-toluidide] and 1.0 kg ha^{-1} of Atrazine [6-chloro-*N*2-ethyl-*N*4-isopropyl-1,3,5-triazine-2,4-diamine] – and soybean – 1.4 kg ha^{-1} of Roundup, 1.4 kg ha^{-1} of Dual II and 0.5 kg ha^{-1} of Sencor [4-amino-6-tert-butyl-4,5-dihydro-3-methylthio-1,2,4-triazin-5-one]. A Triple K cultivator and packer were used in spring before planting of either corn or soybean.

Chisel plough tillage was conducted after harvest. Three parallel 104 mm diameter tile drains ran along the length of the plot at a depth of 0.8 m and 3.8 m spacing, on a slope of 0.1-0.5%. This plot was isolated to prevent flow from the adjacent plots by: (i) a double layer of 0.1016 mm (4 mil) thick plastic barrier installed from the surface to a depth of 1.2 m on three sides, with the open side being available for collection of surface runoff; and (ii) a 7.5 m wide by 67 m long buffer area with a single drain to prevent plot cross contamination. Surface runoff and tile drainage delivered to the instrumentation building were collected by catch basins and automatically recorded by a water meter. Analog and digital pulse signals were sent by the water meter to a multi-channel data logger to monitor, measure, and store water volumes (Tan et al., 1993). To reflect the reality of P loss, water samples collecting periods were scheduled based on agronomic practices and forecasted precipitation (Tan and Zhang, 2011; Zhang et al., 2015a), which resulted in a total of 17 water sampling periods during Jun/2008 to Dec/2011 (Figs. 1 and 2).

Weather data (maximum and minimum temperatures, precipitation, wind speed, relative humidity and solar radiation) were collected at a weather station located about 500 m from the experimental site. Annual average ET_p in Harrow, ON, was obtained from Fallow et al. (2003).

2.2. The EPIC model

EPIC is a process-based field-scale model which simulates physico-

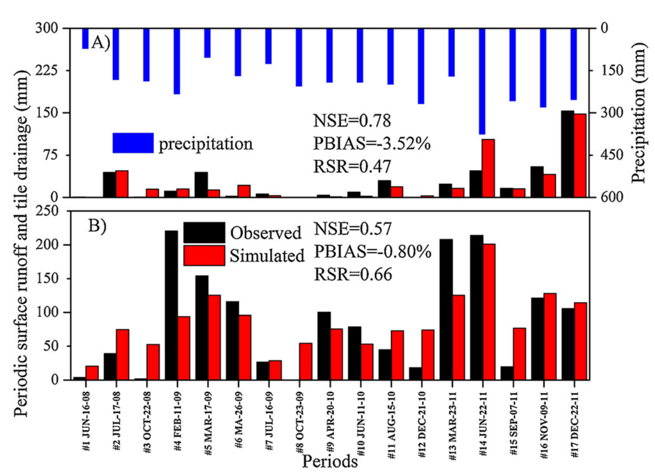

Fig. 1. Natural precipitation and observed and simulated periodic (A) surface runoff and (B) tile drainage flow volumes in 17 water sampling periods during Jun/2008 to Dec/2011.